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Lunar Silane Impact Upon Lunar Oxygen Production Logistics

(NASA-CR-188267) LUNAR SILANE IMPACT UPON LUNAR OXYGEN PRODUCTION LOGISTICS (Eagle Engineering) 104 p

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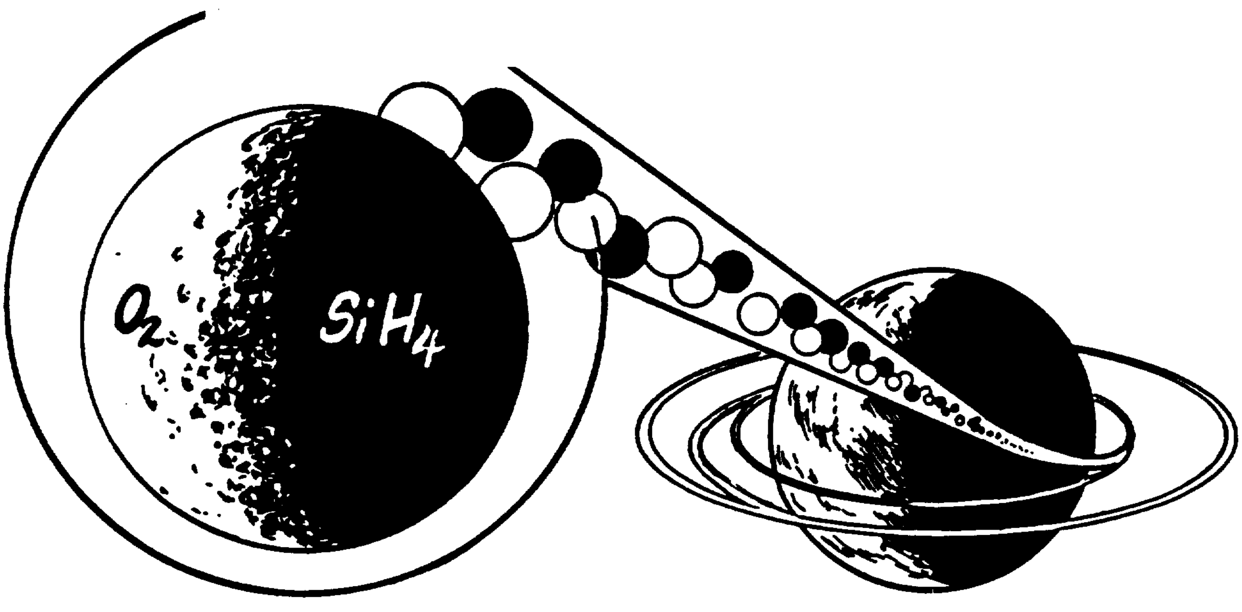

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Nasa CR - 188267

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Lunar Oxygen Production Logistics

Abstract:

A study was accomplished on the impact of producing and utilizing silane (SiH_4) on the Moon as a rocket fuel for a lunar module rather than using Earth-supplied hydrogen. Several chemical reactions were identified which are potentially useful for this work. Although only 1/8 of the silane mass is Earth-supplied hydrogen, the limitations of rocket engine design appear to dissipate most of the potential benefits of silane as a lunar module fuel. A "scenario analysis" was completed on a Lunar Surface Base to Lunar Orbit Space Station mission series and the silane fuel rocket was found to produce a 10 fold gain in mass in lunar orbit over that supplied to the surface from lunar orbit. The previous H_2/O_2 lunar module scenario produced a 9.75 gain. The two approaches are thus nearly equivalent within the limitations of this study. Multi-stage lunar modules and more work upon rocket engine parameters and stage mass may improve this assessment.

Although no major gains were found by the use of silane, equivalent performance to a hydrogen fueled rocket is considered to be of value since silane may be less vulnerable to venting and transfer losses then hydrogen and appears to offer a useful alternative if needed.

Introduction:

An earlier study of the use of liquid oxygen produced on the Moon from the lunar regolith material (ref. 1) indicated a moderately favorable "mass payback ratio" of 2.35. This figure of merit indicated that for each unit mass of liquid hydrogen transported from a space station in Low Earth Orbit, 2.35 units of lunar-produced liquid oxygen were accrued at the same location. Since this analysis treated only the "steady state" situation where all necessary plant equipment and supplies were in place at the beginning of the "scenario analysis", conventional H_2/O_2 propulsion may prove inadequate to economically utilize the potential of lunar-produced oxygen. Several previous studies (refs. 2, 3, and 4) have addressed the topic using solar electric powered "mass drivers" to transport the unrefined lunar material into orbit for processing. Since no propellants are expended by the "mass driver", much more attractive "mass payback ratios" were predicted than were found using a H_2/O_2 lunar module.

Dr. David Criswell of the University of California, San Diego has suggested (ref. 5) that silane (SiH_4) produced on the Moon (from hydrogen brought from Earth and silicon derived from the lunar material) may offer a more effective rocket fuel for a chemical propulsion "lunar module" than hydrogen alone. The fundamental principal is that the lunar-supplied silicon constitutes 7/8 of the silane mass, effectively "stretching" the precious hydrogen which must be transported from the surface of the Earth.

The purpose of this paper is to address the use of silane in a lunar module and to repeat the vehicle performance synthesis and "scenario analysis" of reference 1 to determine the effects of this fuel substitution. The first step taken was to determine the suitability and expected feasible operating parameters of a rocket propulsion system based upon the propellant combination silane and liquid hydrogen. This work was accomplished by In-Space Propulsion Limited of Sacramento, California. Next, six lunar module mission types were simulated to obtain the payload delivered and propellants consumed in the several possible operational modes. Finally, a series of missions were "flown" and the resultant change of initial "stores" at a Lunar Orbit Space Station (LOSS) and Lunar Surface Base (LSB) computed.

Propulsion System Considerations:

Appendix B is a preliminary treatment of the use of the propellant combination silane/oxygen in a rocket propulsion system. No known engine has yet been built for these propellants nor have earlier works been found giving definitive analytical results of their consideration. The preliminary assessment of In-Space Propulsion Limited reported in Appendix B indicates that a pressure-fed, low chamber pressure engine using silane/oxygen is probably feasible. Reasons for not making a like judgement for the much more attractive, but more complex pump-fed engine may be found in Appendix B.

Propellant chemistry dictates a much lower oxidizer to fuel (O/F) mass ratio for silane/oxygen than for hydrogen/oxygen: 1.65:1 vs. 7:1. This is unfortunate, as the motivation for the use of silane is to reduce the use of hydrogen for propulsion and a much higher O/F ratio would be preferred. The maximum possible gain is therefore reduced to 1.89X even though silane is 7/8 silicon, available from lunar materials.

The second rocket propulsion system "figure of merit" addressed in Appendix B was "specific impulse", the ratio of thrust produced to propellant mass flow rate. Although detailed combustion kinetic analyses are required to predict precisely the performance of a rocket propellant pair, similarity of silanes to their carbon-bearing relatives indicates that a specific impulse of about 345 lbf.sec./lbm. may be expected to be delivered by a low chamber pressure silane-fueled engine. The present Space Shuttle Main Engine (SSME) delivers a specific impulse above 450 sec. and the advanced expander cycle engine studied by Aerojet, Rocketdyne and Pratt & Whitney indicates that a specific impulse of about 480 sec. can be achieved for this new design engine by the use of a very high expansion ratio nozzle. Again, the predicted performance of the silane engine suffers when compared to one using hydrogen fuel, further reducing the potential gain from the use of silane.

The influence of the conclusion that a silane-fueled engine must be pressure-fed extends to the inert mass of the propellant tanks, pressurization system, propellant feed lines and valves. As compared to a pump-fed system as is used for hydrogen/oxygen, the pressure-fed system is much heavier, degrading the potential performance of the rocket vehicle.

Preliminary Comparative Analysis:

To obtain a "feel" for the relative influence of the factors discussed above, a few manual calculations were performed. A stage inert mass scaling law based on our experience was assumed for the two forms of rocket propulsion systems:

Silane Stage Inert Mass:

Ws = stage inert mass, Kg.

Wp = propellant capacity

Wlndg. = maximum mass at lunar touchdown

Ws = 1250 + 0.15 Wp + 0.02 Wlndg.,

Hydrogen Stage Inert Mass:

Ws = 1000 + 0.055 Wp + 0.02 Wlndg. (per ref. 1)

Although computer simulation of vehicle flight performance is necessary to account for such factors as reaction control system (RCS) propellant consumption, payload fluid container mass, etc., the "ideal rocket equation" simplified stage performance analysis can reveal trends. Consider the mission of ascending from the lunar surface to a lunar orbit space station to deliver a maximum payload of lunar-produced oxygen. The ideal rocket equation:

$$\frac{m_i}{m_f} = e^{\left(\frac{\Delta V}{g_o I}\right)}$$

m_i = initial mass on lunar surface

m_f = final mass in lunar orbit

e = natural logarithm base

Δv = velocity increment

I = delivered specific impulse

g_0 = universal gravitational constant

For both vehicles, a velocity increment of about 1906 m/sec. is required to ascend from the lunar surface and effect a rendezvous with the Lunar Orbit Space Station. Both the hydrogen and silane stages are assumed to have a maximum propellant capacity of 28.5 tons. With the delivered specific impulse and stage inert mass scaling described above, the O_2/H_2 vehicle delivers to lunar orbit a payload of 53.4 tons and the silane vehicle delivers a payload 31.3 tons.

The hydrogen fuel must be delivered to the Lunar Surface Base from the surface of the Earth. About 3.6 tons of hydrogen fuel is required per ascent mission of the H_2/O_2 lunar module, disregarding transfer losses and boil-off. Therefore, one ton of hydrogen will deliver about 15 tons (53.4/3.6) of liquid oxygen payload from the lunar surface to lunar orbit.

The silane vehicle, operating at a much lower O/F ratio, requires about 10.8 tons of fuel per mission. Due to the lunar derivation of the silicon component of the silane, only 1.34 tons of hydrogen are used per mission (disregarding possible process losses as well as transfer and venting loses.) Thus, one ton of hydrogen used in a silane fuel stage will place about 23.4 tons (31.3/1.34) of payload into lunar orbit - a 56% improvement.

Since the source of silane is the lunar surface, the vehicle using this fuel must reserve sufficient propellant for a subsequent descent mission to prepare for the next ascent flight. A somewhat larger velocity increment is requied for descent (2100 m/sec.) than is necessary for ascent (1906 m/sec.) to permit hovering flight and a soft lunar touchdown. Since only the empty stage and an empty oxygen payload tank must be returned to the lunar surface for most missions, 5.5 tons of propellant (19% of capacity) must be reserved for descent flight.

The vehicle can thus utilize 23 tons of propellant of the 28.5 ton tank capacity for ascent flight, producing a "payload" of 23.9 tons, 5.5 tons of which is the propellant remaining in the vehicle tanks which must be reserved for descent. 18.4 tons of true payload are thus delivered for the expenditure of a full propellant load acquired on the lunar surface. This results in the delivery of 13.7 tons of oxygen (and tank) to lunar orbit for each ton of lunar surface hydrogen consumed - about 8% less than the hydrogen fuel vehicle can deliver.

This preliminary analysis indicates that the use of silane as fuel for the propulsion system of a lunar module may result in a decrease of payload delivered to lunar orbit per unit mass of hydrogen supplied to the lunar surface from Earth as compared to utilizing the hydrogen directly as fuel.

The added complexity and mass of the lunar base chemical processing plant to produce silane as well as liquid oxygen can be expected to detract further from the appeal of this concept, even though most (87.5%) of the fuel mass is derived from lunar material. Should pump-fed, high chamber pressure, high O/F ratio silane/oxygen engines be later shown to be feasible, this conclusion may be invalidated.

It should also be noted that the conclusion is based upon a single mode, single stage vehicle flown on missions similar to those of the Apollo program. Many other systems possibilities are potentially attractive and some of these may show that the inherent fuel mass benefits of silane produced on the Moon may be realized in mission operations.

Production of Silane from Lunar Materials

Section III of Appendix B and all of Appendix C are assessments of the potential of producing silane from lunar materials. These were done by two individuals, operating independently. Both concluded that there are available chemical reactions which could be utilized for this purpose without indications of large process loss of hydrogen.

As both of these assessments were done under very severe time constraints, more study is indicated to narrow the candidate processes and to develop a step-wise research project plan for exploring their actual potentials using available engineering material and catalysts.

Of particular interest is the discussion of the carbothermal process for production of O_2 and of the potential for an integrated O_2/SiH_4 production plant. This discussion begins on page 38 of Appendix B.

Scenario Analysis:

Appendix A presents the result of computer simulation of a silane fuel lunar module performing various potential missions and of a "mission scenario" illustrating the results at the LOSS and LSB of flying a series of missions. The various missions are identified in Apppendix A by a code number.

For example, Mission 4310 is a descent mission which delivers a maximum payload of liquid hydrogen from the LOSS to LSB. 22.46 tons of liquid hydrogen in a 3.96 ton contianer are delivered to the lunar surface at a cost of 11.12 tons of silane, 18.35 tons of liquid oxygen and 0.38 tons of RCS propellants drawn from the LOSS. This quantity of hydrogen, used as feed stock for the LSB chemical processing plant, produces, at 100% yield, almost 180 tons of silane rocket fuel, sufficient to fully load the lunar module for the next 16 ascent flights carrying lunar-produced liquid oxygen to the LOSS for trans-shipment to Low Earth Orbit via the aerobraking lunar ferry vehicle.

The mission of the lunar surface/lunar module activity is fulfilled by the Mission 4412/4312 pair. Mission 4312 returns the lunar module and an empty payload oxygen container of 0.64 tons mass from the LOSS to the LSB. 5.99 tons of propellant are required to be residual in the vehicle at departure from the LOSS, along with 0.12 tons of RCS propellants obtained from LOSS since these propellants originate from Earth, to accomplish this descent mission. The ascent mission, Mission 4412, consumes 22.51 tons of propellant and 0.42 tons of RCS propellants (from LSB stores) to deliver the oxygen container and 17.73 tons of liquid oxygen to the LOSS. For bookkeeping purposes, the entire main propulsion system propellant load of 29.5 tons is charged to the ascent mission, as both the 18.36 tons of oxygen and 11.12 tons of silane are produced on the Moon and placed in the LSB stores.

As lunar operations proceed, the ascent mission may be utilized to deliver silane from the LSB to the LOSS, permitting each ascent mission to consume a full propellant load of 28.5 tons since the lunar module can now be refueled at the LOSS. Mission 4410 delivers 31.08 tons of liquid oxygen or silane payload contained in a 1.13 ton vessel. In addition to the 28.5 tons of main engine propellant, this mission consumes 0.38 tons of RCS propellants from the LSB stores. If Mission 4410 is used to deliver silane, a single flight provides sufficient rocket fuel to supply 13 descent flights. In this mode, the oxygen required for descent flight is drawn from the LOSS stores, diminishing the payload just delivered.

Lunar Module Operations Scenario Analysis:

For simplicity, the operational scenario considered only the first cycle of lunar module operations and did not address the lunar ferry operations, since the groundrule of this particular study was that the ferry would continue to use hydrogen fuel as was the case in the earlier all H_2/O_2 scenario reported in Reference 1.

Initial stores at the LOSS totalled 58.3 tons, including 11.12 tons of silane brought from Earth to provide for the first descent mission. This first mission (Mission 4310) delivered a full load of hydrogen which was assumed to be immediately converted into silane by combining it with lunar-derived silicon.

Initial stores at the LSB were found to total 585.49 tons, 577.37 tons of LO_2, two flight weight payload oxygen vessels and 6.84 tons of RCS propellants, placed on the lunar surface at the time the plant facilities were established. In actuality, the oxygen would be produced while the lunar operations were proceeding, but this simplifying assumption that all oxygen was on hand at mission initiation does not effect the result.

At the conclusions of 16 round trip missions (Missions 4412-4312), the LSB stores were diminished to 6.29 tons, consisting of empty O_2 and H_2 tanks and 1.69 tons of unused silane (about 15% of that required for one flight). The LOSS stores mass at the end of the 16 missions included 283.68

tons of liquid oxygen, available for refueling the lunar ferry and to provide its payload destined for Low Earth Orbit Space Station.

The "figure of merit" for this scenario, the ratio of LOSS gains to losses, was 10.04 not considering the initial flight load of silane and 7.07 if that mass is considered. For the mature operation, the influence of this initial silane would be diminished and the LOSS mass ratio would approach 10.

Since the same "figure of merit" at the LOSS for the H_2/O_2 vehicle of Reference 1 eas 9.75, the two lunar modules perform in essentially an equivalent manner. This indicates that the use of silane produces no significant gains over the use of hydrogen as fuel, within the limits of this particular set of vehicle and scenario assumptions. This result is somewhat improved over the preliminary corporation analysis. Of perhaps equal importance, the use of silane did not prove to be markedly <u>inferior</u> to the use of the much higher performance (O/F ratio and Isp) H_2/O_2 rocket, in spite of the much heavier vehicle mass assumed to be a consequence of the pressure-fed engine constraint. For this reason, the Silane option is considered to be a useful means of insuring against degradation of the Reference 1 approach as the impact of venting and transfer losses and other potential detrimental factors become known. The higher boiling temperature of silane and its high density, as compared to liquid hydrogen, should render the silane approach more forgiving of the penalties which more detailed analyses may identify. A return to the two stage vehicle concept as used in the

Apollo lunar module, rather than the single stage vehicle assumed in this analysis and that of Reference 1, may permit a silane fueled first stage to operate from the Moon in a sub-orbital mode, relieving the early boost phase burdens from a hydrogen fuel second stage and reducing the penalties of returning an empty vehicle to the LSB. This mission mode is schematically illustrated by Figure 1.

A more detailed look is needed at the upper bounds of permissible O/F ratio, chamber pressure (the compactness of the engine), and expansion ratio (for maximum Isp in the vacuum in the lunar vicinity) of a silane/ oxygen rocket engine. Perhaps equally important, innovative means need to be devised for acquiring the benefits to the propellant storage and supply systems mass of the pump-fed engine. To do this the apparent barriers to using conventional pumps brought about by the nature of silane and its combustion products must be overcome.

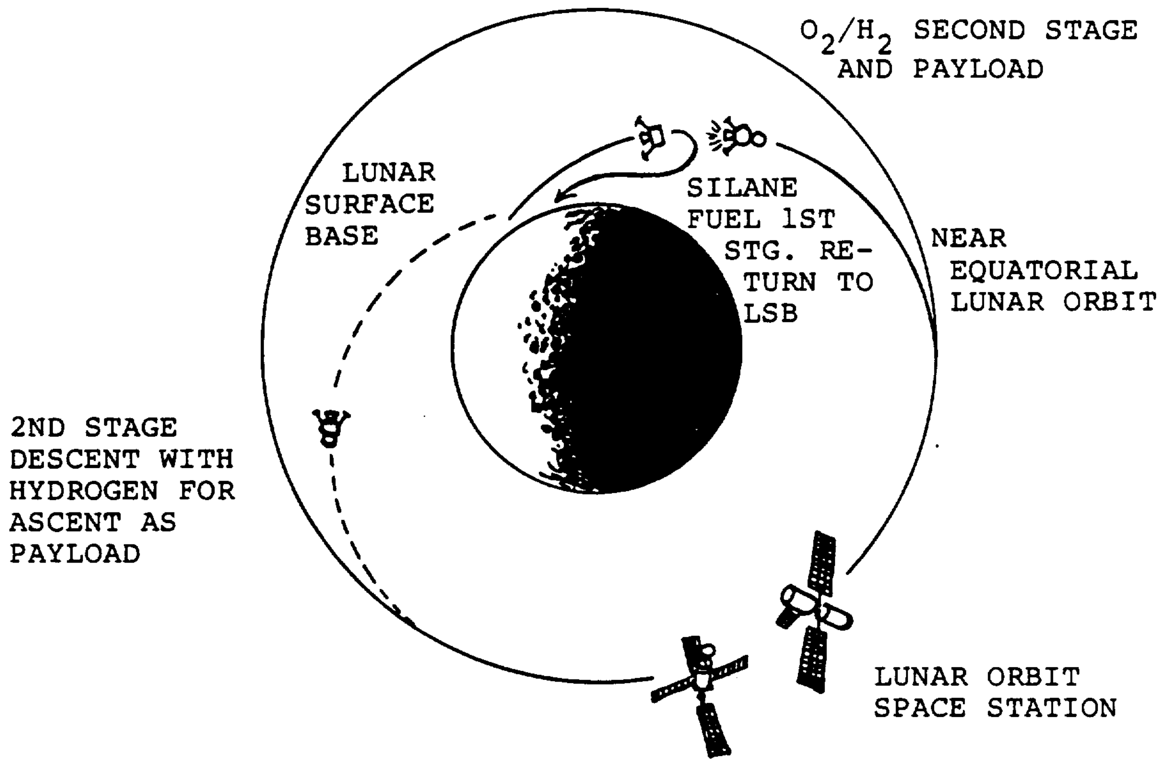

FIGURE 1

TWO-STAGE LUNAR MODULE CONCEPT

SILANE FUEL FIRST STAGE

Postscript

As an added piece of information, two additional silane lunar module missions were synthesized using a more optimistic stage mass scaling law (10% proportionately factor of inertness to propellant capacity rather than 15%) and a higher delivered specific impulse (350 sec. rather than 345 sec.). Mission 4316 showed a reduction from 5.99 to 4.63 tons of propellant required to be reserved for descent flight. This and the assumption of improved engine and stage properties permitted mission 4416 to deliver 22.95 tons of LO_2 per ascent mission rather than the 17.73 tons of LO_2 delivered by Mission 4412--a 29% improvement. These missions are described in Appendix A. Due to lack of time, these more optimistic lunar module missions were not used to rerun the "Scenario Analysis".

References

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SILANE FUEL LUNAR MODULE

MISSION SYNTHESIS

AND

SCENARIO ANALYSIS

APPENDIX A

LUNAR RESEARCH CENTER SUPPORT
OTV PERFORMANCE

Case No.	4316.00	SILANE LUNAR MODULE	Oct. 8, 1983
For:	CAL SPACE		H. P. Davis
Sep.Mass,#	22651.08	ET-ACC OTV LUNAR MODULE	Empty LM+ 02 tank Del
Total Thrs	30000.00	Best Case	LO S/S toLunarSurface
Init. T/W	1.32	Uses residuals fr.4416	Pressure-fed Engines
Propellant:	02/Silane @ O/F = 1.80		Mass Ratio @ Isp =
Quantity,#	65000.00	,% LAMBDA = 86.20	350.00 MPS,RCS=.6x

	ΔV, ft/sec	Mass Ratio
Separation from LO S/S - RCS	2.00	1.00
Descent Orbit Injection - MPS	65.10	1.01
Powered Descent Initiation - MPS	6764.00	1.82
Attitude Control during desc.-RCS	60.00	1.01
Descent Venting Loss - MPS,(Zero)	0.00	
Descent Venting Loss - P/L, lbm	0.00	

Venting & Transfer Loss @ Moon,lbm 0.00 (Zero)

Stage Inert Mass, lbm. 10405.00 (Input algorithm)

		T/W lunar
Arrival Mass, lbm. (Empty LM + 02 tank)	12235.00	14.71
Arrival Payload, lbm.	1830.00	
Net Useful Payload @ LS, lbm.	1830.00	Empty LO2
Payload loaded @ LO S/S, lbm.	1830.00	tank only

Mission Mass Time History	End burn	Prop. Used
Arrival on Lunar Surface	12235.00	
Powered Descent - MPS	12235.00	10079.65
Attitude Control - RCS	22314.65	199.14
Descent Orbit Injection - MPS	22513.78	130.59
Separation from LO S/S - RCS	22644.38	6.71
Departure Mass from LO S/S, lbm.	22651.08	

Total MPS Propellant Consumed, lbm	10210.24	15.71
MPS Capacity, lbm	65000.00	% full
MPS Propellant Capacity not utilized	54789.76	
Total RCS Propellant Consumed, lbm.	205.84	

Lunar-Supplied Silane reqd. @ LO resid. in tnk	3646.51	from prev.
Lunar-Supplied LO2 required @ LO resid. in tnk	6563.73	LO2 deliver
Total RCS Propellant Consumed, lbm	205.84	mission

Notes: ΔV from Apollo 17 + 2% FPR — 8.08% of Lun.Orb
Inert Mass = 2205 +0.10Wp +2% Touchdown Wt. — Departure Mass
Zero transfer losses — is Useful P/L @LS

LUNAR RESEARCH CENTER SUPPORT
OTV PERFORMANCE

Case No.	4416.00	SILANE FUEL	Oct. 8, 1983
For:	CAL-SPACE	(reserve propellant for Descent)	H. P. Davis
Sep.Mass,#	128561.94	ET-ACC OTV LUNAR MODULE	Payload Delivery from
Total Thrs	30000.00	Best Case	LSB to Lunar Orb. S/S
Init. T/W	1.40 (lunar)		4 Pressure Fed Engines
Propellant:	O2/Silane @ O/F= 1.80		Mass Ratio @ Isp =
Quantity,#	65000.00	% LAMBDA = 86.20	350.00 MPS,RCS=.6x

	ΔV, ft/sec	Mass Ratio
Ascent Flight 48.5x9.1 NM - MPS	6197.00	1.73
Vernier Adjustment RCS	10.00	1.00
Attitude Control during asc.- RCS	25.00	1.00
Ascent Venting Loss - MPS,(Zero)	0.00	
Ascent Venting Loss - P/L, lbm	0.00	
Terminal Phase Initiation - MPS	55.00	1.00
Circularization to 59 x 59 nm -RCS	5.00	1.00
Rendevous & Dock w/ LO Spa.St.-RCS	25.00	1.00

Venting & Transfer Loss @LOS/S,lbm 0.00 (Assumption)

Stage Inert Mass, lbm. 10405.00 (Input)

Arrival Mass, lbm. (Trial Input -Iterate)	73063.90	
Arrival Payload, lbm.	52448.66	
Net Useful Payload @ LOSS, lbm.	52448.66	******
Payload loaded @ LSB, lbm.	52448.66	

Mission Mass Time History	End burn	Prop. Used
Arrival at Lunar Orbit Space Sta.	73063.90	
Circularization, Rend.& Dock - RCS	73063.90	325.09
Terminal Phase Initiation - MPS	73388.99	359.49
Attitude Control - RCS	73748.47	273.51
Vernier Adjustment - RCS	74021.99	109.69
Ascent Flight - MPS	74131.67	54430.27
Departure Mass from Lunar Surface	128561.94	

Total MPS Propellant Consumed, lbm	54789.76	
MPS Capacity, lbm	65000.00	
MPS Propellant Residual, lbm. (Iterate to Wpd)	10210.24	10210.24
Total RCS Propellant Consumed, lbm.	708.29	target Wpd
		0.00
Lunar Surface Supplied Silane required	23214.29	variance
Lunar-Supplied LO2 required @ LSB w/o P/L	41785.71	
Total RCS Propellant Supplied @LSB	708.29	

Notes: ΔV from Apollo 17 + 2% FPR

40.80 % of LSB Departure Mass is Useful P/L @LO

Does NOT Require Silane & LO2 service for return

LUNAR RESEARCH CENTER SUPPORT

SILANE FUEL ORBIT TRANSFER VEHICLE MISSION PERFORMANCE

Case Number:	4316.00 Lunar Module Descent	Best Case	Oct. 8, 1983
Mission Departure from:	LO Space Station		
Mission Destination to:	Lunar Surface Base	OTV Prop.Req	4.63
Return to Origin on this Mission?	No	OTV B/O Mass	4.72
Mission objective:	Deliver LM + Empty O2 Tank only to lunar surface	MPS Eng. Isp	350.00
		O/F Ratio	1.80
	T/W lunar = 14.71	Total Th.,kN	6.74

Mission Sequence Mass History,Tonnes		ΔVelocity Maneauvers Required, meters/sec. MPS	OMS	RCS
1. Separ. from LO S/S	10.27			0.61
2. Descent Orbit Insert	10.27	19.85		
3. Powered Descent Flt.	10.21	2062.20		
4. Lunar Approach	10.12			18.29
5. Lunar Surface Base	5.55			
6. Total useful Payload	0.83			
7. Ascent LO2 P/L tank	0.83	for return of lunar O2 to LOSS		
8. LH2+Tank Payload	0.00			
9. Net LH2 Payload @0.9	0.00	LH2 tanks =	0.00 tonnes	
10 LH2 for LM Return LO	0.00			
11. LH2 to support LSB	0.00	******		
12. Total LH2 @ LO reqd	0.00	Delivered to LO S/S by Lunar Ferry		
13. Total LO2 @ LO reqd	2.98	Delivered by previous LM mission		
14. Total RCS @ LO reqd	0.09	Delivered to LO S/S by Lunar Ferry		
15. Total Silane @ LO rq	1.65	Delivered by previous LM mission		

Notes: BEST Case Inert Mass = 1000+.10*Wp +.02*Max Ldg. Wt., Kg.
Transfer & Vent Loss = 0 (Assumption)
Tank mass = 10 % H2, 3.5 % O2

LUNAR RESEARCH CENTER SUPPORT

SILANE FUEL ORBIT TRANSFER VEHICLE MISSION PERFORMANCE

Case Number: 4416.00 Lunar Module Ascent - Best Case		Oct. 8, 1983	
Mission Departure from: Lunar Surface Base			
Mission Destination to: Lunar Orbit Space Sta.		OTV Prop.Req	29.48
Return to Origin on this Mission?	Yes	OTV B/O Mass	4.72
Mission objective:	Deliver LO2 payload to Lunar Orbit Space Station	MPS Eng. Isp	350.00
		O/F Ratio	1.80
(Reserve Des.Wp) Lunar Surface T/W =	1.40	Total Th.,kN	6.74

Mission Sequence	Mass History, Tonnes	ΔVelocity Maneauvers Required, meters/sec. MPS	OMS	RCS
1. Departure from LSB	58.30			
2. Ascent Flight	58.30	1889.33		
3. Ascent Orbit	33.57			10.67
4. Terminal Phase	33.45	16.77		9.15
5. Lunar Orbit Spa. Sta	33.14			
6. Total useful Payload	23.79			
7. Crew Module + Crew	0.00			
8. LO2+Tank Payload	23.79			
9. Net LO2 Payload@.965	22.95	LO2 tanks =	0.83 tonnes	
10 LO2 for LM Return LS	0.00	already accounted for		
11. LO2 for LOSS Stores	22.95	******	output of mission	
12. Total Silane @ LSB	10.53	Produced on the Moon, LM suppl LH2		
13. Total LO2 @ LSB reqd	41.90	From LSB Stores, produced on Moon		
14. Total RCS @ LSB reqd	0.32	not incl. descent flight needs.		

Notes: Inert Mass = 1000 + 10 % Wp + 2% Lndg. Wt.
Vent & Transfer Losses = Zero (assumption)
Tank Mass = 10% H2, 3.5% O2

NO lunar orbit servicing req'd.

LUNAR RESEARCH CENTER SUPPORT
OTV PERFORMANCE

Case No. 4310.00	SILANE LUNAR MODULE		Oct. 1, 1983
For: CAL SPACE			H. P. Davis
Sep.Mass,# 142721.84	ET-ACC OTV LUNAR MODULE	Payload Delivery from	
Total Thrs 30000.00	Best Case	LO S/S to LunarSurface	
Init. T/W 0.21		4 Pressure-Fed Engines	
Propellant: O2/Silane @ O/F = 1.65		Mass Ratio @ Isp =	
Quantity,# 65000.00 ,% LAMBDA =	82.24	345.00 MPS,RCS=.6x	

	ΔV, ft/sec	Mass Ratio
Separation from LO S/S - RCS	2.00	1.00
Descent Orbit Injection - MPS	65.10	1.01
Powered Descent Initiation - MPS	6764.00	1.84
Attitude Control during desc.-RCS	60.00	1.01
Descent Venting Loss - MPS,(Zero)	0.00	
Descent Venting Loss - P/L, lbm	0.00	

Venting & Transfer Loss @ Moon,lbm 0.00 (Zero)

Stage Inert Mass, lbm. 14034.37 (Input algorithm)

		T/W lunar
Arrival Mass, lbm. (Trial Input -Iterate)	76406.24	2.36
Arrival Payload, lbm.	62371.87	
Net Useful Payload @ LS, lbm.	62371.87	******
Payload loaded @ LO S/S, lbm.	62371.87	

Mission Mass Time History	End burn	Prop. Used
Arrival on Lunar Surface	76406.24	
Powered Descent - MPS	76406.24	64165.27
Attitude Control - RCS	140571.51	1272.72
Descent Orbit Injection - MPS	141844.23	834.73
Separation from LO S/S - RCS	142678.96	42.87
Departure Mass from LO S/S, lbm.	142721.84	

Total MPS Propellant Consumed, lbm	65000.00	100.00
MPS Capacity, lbm	65000.00	% full
MPS Propellant Residual, lbm. (Iterate to 0)	0.00	
Total RCS Propellant Consumed, lbm.	1315.60	

Lunar-Supplied Silane reqd. @ LO not incl P/L	24528.30
Lunar-Supplied LO2 required @ LO	40471.70
Total RCS Propellant Consumed, lbm	1315.60

Notes: ΔV from Apollo 17 + 2% FPR — 43.70% of Lun.Orb
Inert Mass = 2706 +0.15Wp +2% Touchdown Wt. — Departure Mass
Zero transfer losses — is Useful P/L @LS

LUNAR RESEARCH CENTER SUPPORT
OTV PERFORMANCE

Case No.	4312.00	SILANE LUNAR MODULE	Oct. 1, 1983
For:	CAL SPACE		H. P. Davis
Sep.Mass,#	29017.18	ET-ACC OTV LUNAR MODULE	Empty LM+ 02 tank Del
Total Thrs	30000.00	Best Case	LO S/S toLunarSurface
Init. T/W	1.03	Uses residuals fr.4412	Pressure-fed Engines
Propellant:	02/Silane ● O/F = 1.65		Mass Ratio ● Isp =
Quantity,#	65000.00	,% LAMBDA = 82.24	345.00 MPS,RCS=.6x

	ΔV, ft/sec	Mass Ratio
Separation from LO S/S - RCS	2.00	1.00
Descent Orbit Injection - MPS	65.10	1.01
Powered Descent Initiation - MPS	6764.00	1.84
Attitude Control during desc.-RCS	60.00	1.01
Descent Venting Loss - MPS,(Zero)	0.00	
Descent Venting Loss - P/L, lbm	0.00	

Venting & Transfer Loss ● Moon,lbm 0.00 (Zero)

Stage Inert Mass, lbm. 14034.37 (Input algorithm from 4310)

		T/W lunar
Arrival Mass, lbm. (Empty LM + 02 tank)	15534.37	11.59
Arrival Payload, lbm.	1500.00	
Net Useful Payload ● LS, lbm.	1500.00	Empty LO2
Payload loaded ● LO S/S, lbm.	1500.00	tank only

Mission Mass Time History	End burn	Prop. Used
Arrival on Lunar Surface	15534.37	
Powered Descent - MPS	15534.37	13045.62
Attitude Control - RCS	28579.99	258.76
Descent Orbit Injection - MPS	28838.75	169.71
Separation from LO S/S - RCS	29008.47	8.72
Departure Mass from LO S/S, lbm.	29017.18	

Total MPS Propellant Consumed, lbm	13215.33	20.33
MPS Capacity, lbm	65000.00	% full
MPS Propellant Capacity not utilized	51784.67	
Total RCS Propellant Consumed, lbm.	267.48	

Lunar-Supplied Silane reqd. ● LO resid. in tnk	4986.92	from prev.
Lunar-Supplied LO2 required ● LO resid. in tnk	8228.42	LO2 deliver
Total RCS Propellant Consumed, lbm	267.48	mission

Notes: ΔV from Apollo 17 + 2% FPR
Inert Mass = 2706 +0.15Wp +2% Touchdown Wt.
Zero transfer losses

5.17% of Lun.Orb Departure Mass is Useful P/L ●LS

LUNAR RESEARCH CENTER SUPPORT
OTV PERFORMANCE

Case No.	4314.00	SILANE LUNAR MODULE	Oct. 1, 1983
For:	CAL SPACE		H. P. Davis
Sep.Mass,#	29022.79	ET-ACC OTV LUNAR MODULE	Lunar Module & O2 tank
Total Thrs	30000.00	Best Case	LO S/S to LunarSurface
Init. T/W	1.03		4 Pressure-Fed Engines
Propellant:	O2/Silane @ O/F = 1.65		Mass Ratio @ Isp =
Quantity,#	65000.00 ,% LAMBDA =	82.24	345.00 MPS,RCS=.6x

	ΔV, ft/sec	Mass Ratio
Separation from LO S/S - RCS	2.00	1.00
Descent Orbit Injection - MPS	65.10	1.01
Powered Descent Initiation - MPS	6764.00	1.84
Attitude Control during desc.-RCS	60.00	1.01
Descent Venting Loss - MPS,(Zero)	0.00	
Descent Venting Loss - P/L, lbm	0.00	

Venting & Transfer Loss @ Moon,lbm 0.00 (Zero)

Stage Inert Mass, lbm. 14037.37 (Input algorithm)

		T/W lunar
Arrival Mass, lbm. (Trial Input -Iterate)	15537.37	11.58
Arrival Payload, lbm.	1500.00	
Net Useful Payload @ LS, lbm.	1500.00	******
Payload loaded @ LO S/S, lbm.	1500.00	LO2 tank

Mission Mass Time History	End burn	Prop. Used
Arrival on Lunar Surface	15537.37	
Powered Descent - MPS	15537.37	13048.14
Attitude Control - RCS	28585.51	258.81
Descent Orbit Injection - MPS	28844.32	169.74
Separation from LO S/S - RCS	29014.07	8.72
Departure Mass from LO S/S, lbm.	29022.79	

Total MPS Propellant Consumed, lbm	13217.89	20.34
MPS Capacity, lbm	65000.00	% full
MPS Propellant Capacity unused, lbm.	51782.11	
Total RCS Propellant Consumed, lbm.	267.53	

Lunar-Supplied Silane reqd. @ LO not incl P/L	4987.88
Lunar-Supplied LO2 required @ LO	8230.00
Total RCS Propellant Consumed, lbm	267.53

Notes: ΔV from Apollo 17 + 2% FPR — 5.17% of Lun.Orb
Inert Mass = 2706 +0.15Wp +2% Touchdown Wt. — Departure Mass
Zero transfer losses — is Useful P/L @LS

LUNAR RESEARCH CENTER SUPPORT
OTV PERFORMANCE

Case No.	4410.00	SILANE FUEL	Oct. 1, 1983
For:	CAL-SPACE		H. P. Davis
Sep.Mass,#	150891.06	ET-ACC OTV LUNAR MODULE Payload Delivery from	
Total Thrs	30000.00	Best Case	LSB to Lunar Orb. S/S
Init. T/W	1.19 (lunar)		4 Pressure Fed Engines
Propellant:	O2/Silane @ O/F= 1.65		Mass Ratio @ Isp =
Quantity,#	65000.00	% LAMBDA = 82.24	345.00 MPS,RCS=.6x

	ΔV, ft/sec	Mass Ratio
Ascent Flight 48.5x9.1 NM - MPS	6197.00	1.75
Vernier Adjustment RCS	10.00	1.00
Attitude Control during asc.- RCS	25.00	1.00
Ascent Venting Loss - MPS,(Zero)	0.00	
Ascent Venting Loss - P/L, lbm	0.00	
Terminal Phase Initiation - MPS	55.00	1.00
Circularization to 59 x 59 nm -RCS	5.00	1.00
Rendevous & Dock w/ LO Spa.St.-RCS	25.00	1.00

Venting & Transfer Loss @LOS/S,lbm 0.00 (Assumption)

Stage Inert Mass, lbm. 14034.37 (Input)

Arrival Mass, lbm. (Trial Input -Iterate)	85054.50	
Arrival Payload, lbm.	71020.13	
Net Useful Payload @ LOSS, lbm.	71020.13	******
Payload loaded @ LSB, lbm.	71020.13	

Mission Mass Time History	End burn	Prop. Used
Arrival at Lunar Orbit Space Sta.	85054.50	
Circularization, Rend.& Dock - RCS	85054.50	383.93
Terminal Phase Initiation - MPS	85438.43	424.59
Attitude Control - RCS	85863.02	323.06
Vernier Adjustment - RCS	86186.09	129.57
Ascent Flight - MPS	86315.65	64575.41
Departure Mass from Lunar Surface	150891.06	

Total MPS Propellant Consumed, lbm	65000.00
MPS Capacity, lbm	65000.00
MPS Propellant Residual, lbm. (Iterate to 0)	0.00
Total RCS Propellant Consumed, lbm.	836.56
Lunar Surface Supplied Silane required	24528.30
Lunar-Supplied LO2 required @ LSB w/o P/L	40471.70
Total RCS Propellant Supplied @LSB	836.56

Notes: ΔV from Apollo 17 + 2% FPR

Requires Silane & LO2 service for return

47.07 % of LSB Departure Mass is Useful P/L @LO

LUNAR RESEARCH CENTER SUPPORT
OTV PERFORMANCE

Case No. 4412.00 SILANE FUEL Oct. 1, 1983
For: CAL-SPACE (reserve propellant for Descent) H. P. Davis
Sep.Mass,# 120212.98 ET-ACC OTV LUNAR MODULE Payload Delivery from
Total Thrs 30000.00 Best Case LSB to Lunar Orb. S/S
Init. T/W 1.50 (lunar) 4 Pressure Fed Engines
Propellant: O2/Silane @ O/F= 1.65 Mass Ratio @ Isp =
Quantity,# 65000.00 % LAMBDA = 82.24 345.00 MPS,RCS=.6x

	ΔV, ft/sec	Mass Ratio
Ascent Flight 48.5x9.1 NM - MPS	6197.00	1.75
Vernier Adjustment RCS	10.00	1.00
Attitude Control during asc.- RCS	25.00	1.00
Ascent Venting Loss - MPS,(Zero)	0.00	
Ascent Venting Loss - P/L, lbm	0.00	
Terminal Phase Initiation - MPS	55.00	1.00
Circularization to 59 x 59 nm -RCS	5.00	1.00
Rendevous & Dock w/ LO Spa.St.-RCS	25.00	1.00

Venting & Transfer Loss @LOS/S,lbm 0.00 (Assumption)

Stage Inert Mass, lbm. 14034.37 (Input)

Arrival Mass, lbm. (Trial Input -Iterate)	67761.83	
Arrival Payload, lbm.	40512.13	
Net Useful Payload @ LOSS, lbm.	40512.13	******
Payload loaded @ LSB, lbm.	40512.13	

Mission Mass Time History	End burn	Prop. Used
Arrival at Lunar Orbit Space Sta.	67761.83	
Circularization, Rend.& Dock - RCS	67761.83	305.87
Terminal Phase Initiation - MPS	68067.70	338.27
Attitude Control - RCS	68405.97	257.38
Vernier Adjustment - RCS	68663.35	103.22
Ascent Flight - MPS	68766.57	51446.40
Departure Mass from Lunar Surface	120212.98	

Total MPS Propellant Consumed, lbm	51784.67	
MPS Capacity, lbm	65000.00	
MPS Propellant Residual, lbm. (Iterate to Wpd)	13215.33	13215.33
Total RCS Propellant Consumed, lbm.	666.48	target Wpd

Lunar Surface Supplied Silane required	24528.30
Lunar-Supplied LO2 required @ LSB w/o P/L	40471.70
Total RCS Propellant Supplied @LSB	666.48

Notes: ΔV from Apollo 17 + 2% FPR — 33.70 % of LSB Departure Mass is Useful P/L @LO

Does NOT Require Silane & LO2 service for return

LUNAR RESEARCH CENTER SUPPORT
OTV PERFORMANCE

Case No. 4414.00	SILANE FUEL		Oct. 1, 1983
For: CAL-SPACE			H. P. Davis
Sep.Mass,# 24897.69	ET-ACC OTV LUNAR MODULE		Lunar Moduule only fr.
Total Thrs 30000.00	Best Case		LSB to Lunar Orb. S/S
Init. T/W 7.23 (lunar)			4 Pressure Fed Engines
Propellant: O2/Silane ● O/F= 1.65			Mass Ratio ● Isp =
Quantity,# 65000.00	% LAMBDA =	82.24	345.00 MPS,RCS=.6x

	ΔV, ft/sec	Mass Ratio
Ascent Flight 48.5x9.1 NM - MPS	6197.00	1.75
Vernier Adjustment RCS	10.00	1.00
Attitude Control during asc.- RCS	25.00	1.00
Ascent Venting Loss - MPS,(Zero)	0.00	
Ascent Venting Loss - P/L, lbm	0.00	
Terminal Phase Initiation - MPS	55.00	1.00
Circularization to 59 x 59 nm -RCS	5.00	1.00
Rendevous & Dock w/ LO Spa.St.-RCS	25.00	1.00

Venting & Transfer Loss ●LOS/S,lbm 0.00 (Assumption)

Stage Inert Mass, lbm. 14034.37 (Input)

Arrival Mass, lbm. (Trial Input -Iterate)	14034.37
Arrival Payload, lbm.	0.00
Net Useful Payload ● LOSS, lbm.	0.00
Payload loaded ● LSB, lbm.	0.00

Mission Mass Time History	End burn	Prop. Used
Arrival at Lunar Orbit Space Sta.	14034.37	
Circularization, Rend.& Dock - RCS	14034.37	63.35
Terminal Phase Initiation - MPS	14097.72	70.06
Attitude Control - RCS	14167.78	53.31
Vernier Adjustment - RCS	14221.09	21.38
Ascent Flight - MPS	14242.47	10655.23
Departure Mass from Lunar Surface	24897.69	

Total MPS Propellant Consumed, lbm	10725.29
MPS Capacity, lbm	65000.00
MPS Propellant Capacity unused, lbm.	54274.71
Total RCS Propellant Consumed, lbm.	138.04
Lunar Surface Supplied Silane required	4047.28
Lunar-Supplied LO2 required ● LSB w/o P/L	6678.01
Total RCS Propellant Supplied ●LSB	138.04

Notes: ΔV from Apollo 17 + 2% FPR — 0.00 % of LSB Departure Mass is Useful P/L ●LO

Requires Silane & LO2 service for return

LUNAR RESEARCH CENTER SUPPORT
SILANE FUEL ORBIT TRANSFER VEHICLE MISSION PERFORMANCE

Case Number: 4310.00 Lunar Module Descent	Best Case		Oct. 1, 1983
Mission Departure from: LO Space Station			
Mission Destination to: Lunar Surface Base		OTV Prop.Req	29.48
Return to Origin on this Mission? No		OTV B/O Mass	6.36
Mission objective: Deliver LM + Maximum		MPS Eng. Isp	345.00
Payload to lunar surface		O/F Ratio	1.65
T/W lunar =	2.36	Total Th.,kN	6.74

Mission Sequence	Mass History,Tonnes	ΔVelocity Maneauvers Required, meters/sec. MPS	OMS	RCS
1. Separ. from LO S/S	64.73			0.61
2. Descent Orbit Insert	64.71	19.85		
3. Powered Descent Flt.	64.33	2062.20		
4. Lunar Approach	63.75			18.29
5. Lunar Surface Base	34.65			
6. Total useful Payload	28.29			
7. Ascent LO2 P/L tank	1.86	for return of lunar O2 to LOSS		
8. LH2+Tank Payload	26.43			
9. Net LH2 Payload@0.85	22.46	LH2 tanks =	3.96 tonnes	
10 LH2 for LM Return LO	0.00			
11. LH2 to support LSB	22.46	******	output of mission	
12. Total LH2 @ LO reqd	22.46	Delivered to LO S/S by Lunar Ferry		
13. Total LO2 @ LO reqd	18.35	Delivered by previous LM mission		
14. Total RCS @ LO reqd	0.60	Delivered to LO S/S by Lunar Ferry		
15. Total Silane @ LO rq	11.12	Delivered by previous LM mission		

Notes: Nom. Case Inert Mass = 1250+.15*Wp +.02*Ldg.Wt., Kg.
Transfer & Vent Loss = 0 (Assumption)
Tank mass = 15% H2, 3.5% O2

LUNAR RESEARCH CENTER SUPPORT
SILANE FUEL ORBIT TRANSFER VEHICLE MISSION PERFORMANCE

Case Number: 4312.00 Lunar Module Descent	Best Case	Oct. 1, 1983	
Mission Departure from: LO Space Station			
Mission Destination to: Lunar Surface Base	OTV Prop.Req		5.99
Return to Origin on this Mission? No	OTV B/O Mass		6.36
Mission objective: Deliver LM + Empty O2	MPS Eng. Isp		345.00
Tank only to lunar surface	O/F Ratio		1.65
T/W lunar = 11.59	Total Th.,kN		6.74

Mission Sequence	Mass History, Tonnes	ΔVelocity Maneauvers Required, meters/sec. MPS	OMS	RCS
1. Separ. from LO S/S	13.16			0.61
2. Descent Orbit Insert	13.16	19.85		
3. Powered Descent Flt.	13.08	2062.20		
4. Lunar Approach	12.96			18.29
5. Lunar Surface Base	7.05			
6. Total useful Payload	0.68			
7. Ascent LO2 P/L tank	0.64	for return of lunar O2 to LOSS		
8. LH2+Tank Payload	0.04			
9. Net LH2 Payload@0.85	0.03	LH2 tanks =	0.01 tonnes	
10 LH2 for LM Return LO	0.00			
11. LH2 to support LSB	0.03	******	spurious- ignore	
12. Total LH2 @ LO reqd	0.03	Delivered to LO S/S by Lunar Ferry		
13. Total LO2 @ LO reqd	3.73	Delivered by previous LM mission		
14. Total RCS @ LO reqd	0.12	Delivered to LO S/S by Lunar Ferry		
15. Total Silane @ LO rq	2.26	Delivered by previous LM mission		

Notes: Nom. Case Inert Mass = 1250+.15*Wp +.02*Max Ldg. Wt., Kg.
Transfer & Vent Loss = 0 (Assumption)
Tank mass = 15% H2, 3.5% O2

LUNAR RESEARCH CENTER SUPPORT
SILANE FUEL ORBIT TRANSFER VEHICLE MISSION PERFORMANCE

Case Number: 4314.00 Lunar Module Descent	Best Case	Oct. 1, 1983	
Mission Departure from: LO Space Station			
Mission Destination to: Lunar Surface Base	OTV Prop.Req	5.99	
Return to Origin on this Mission? No	OTV B/O Mass	6.37	
Mission objective: Deliver LM + O2 tank only to lunar surface	MPS Eng. Isp	345.00	
	O/F Ratio	1.65	
T/W lunar = 11.58	Total Th.,kN	6.74	

Mission Sequence Mass History,Tonnes		ΔVelocity Maneauvers Required, meters/sec. MPS	OMS	RCS
1. Separ. from LO S/S	13.16			0.61
2. Descent Orbit Insert	13.16	19.85		
3. Powered Descent Flt.	13.08	2062.20		
4. Lunar Approach	12.96			18.29
5. Lunar Surface Base	7.05			
6. Total useful Payload	0.68			
7. Ascent LO2 P/L tank	0.68	for return of lunar O2 to LOSS		
8. LH2+Tank Payload	0.00			
9. Net LH2 Payload@0.85	0.00	LH2 tanks =	0.00 tonnes	
10 LH2 for LM Return LO	0.00			
11. LH2 to support LSB	0.00	****** output of mission		
12. Total LH2 @ LO reqd	0.00	Delivered to LO S/S by Lunar Ferry		
13. Total LO2 @ LO reqd	3.73	Delivered by previous LM mission		
14. Total RCS @ LO reqd	0.12	Delivered to LO S/S by Lunar Ferry		
15. Total Silane @ LO rq	2.26	Delivered by previous LM mission		

Notes: Best Case Inert Mass = 1250+.15*Wp +.02*Ldg.Wt., Kg.
Transfer & Vent Loss = 0 (Assumption)
Tank mass = 15% H2, 3.5% O2

LUNAR RESEARCH CENTER SUPPORT

SILANE FUEL ORBIT TRANSFER VEHICLE MISSION PERFORMANCE

Case Number: 4410.00 Lunar Module Ascent - Best Case Oct. 1, 1983

Mission Departure from: Lunar Surface Base

Mission Destination to:	Lunar Orbit Space Sta.	OTV Prop.Req	29.48
Return to Origin on this Mission?	No	OTV B/O Mass	6.36
Mission objective:	Deliver LO2 payload	MPS Eng. Isp	345.00
	to Lunar Orbit Space Station	O/F Ratio	1.65
	Lunar Surface T/W = 1.19	Total Th.,kN	6.74

Mission Sequence Mass History,Tonnes		ΔVelocity Maneauvers Required, meters/sec. MPS	OMS	RCS
1. Departure from LSB	68.43			
2. Ascent Flight	68.43	1889.33		
3. Ascent Orbit	39.09			10.67
4. Terminal Phase	38.94	16.77		9.15
5. Lunar Orbit Spa. Sta	38.57			
6. Total useful Payload	32.21			
7. Crew Module + Crew	0.00			
8. LO2+Tank Payload	32.21			
9. Net LO2 Payload@.965	31.08	LO2 tanks = 1.13 tonnes		
10 LO2 for LM Return LS	0.00	reserved for return w/o P/L (est)		
11. LO2 for LOSS Stores	31.08	****** output of mission		
12. Total Silane @ LSB	11.12	Produced on the Moon, LM suppl LH2		
13. Total LO2 @ LSB reqd	49.44	From LSB Stores, produced on Moon		
14. Total RCS @ LSB reqd	0.38			

Notes: Inert Mass = 1250 + 15 % Wp + 2% Lndg. Wt.
Vent & Transfer Losses = Zero (assumption)
Tank Mass = 15% H2, 3.5% O2

LUNAR RESEARCH CENTER SUPPORT

SILANE FUEL ORBIT TRANSFER VEHICLE MISSION PERFORMANCE

Case Number: 4412.00 Lunar Module Ascent - Best Case			Oct. 1, 1983
Mission Departure from: Lunar Surface Base			
Mission Destination to: Lunar Orbit Space Sta.		OTV Prop.Req	29.48
Return to Origin on this Mission? Yes		OTV B/O Mass	6.36
Mission objective: Deliver LO2 payload		MPS Eng. Isp	345.00
to Lunar Orbit Space Station		O/F Ratio	1.65
(Reserve Des.Wp) Lunar Surface T/W =	1.50	Total Th.,kN	6.74

Mission Sequence Mass History,Tonnes		ΔVelocity Maneauvers Required, meters/sec. MPS	OMS	RCS
1. Departure from LSB	54.52			
2. Ascent Flight	54.52	1889.33		
3. Ascent Orbit	31.14			10.67
4. Terminal Phase	31.02	16.77		9.15
5. Lunar Orbit Spa. Sta	30.73			
6. Total useful Payload	18.37			
7. Crew Module + Crew	0.00			
8. LO2+Tank Payload	18.37			
9. Net LO2 Payload@.965	17.73	LO2 tanks =	0.64 tonnes	
10 LO2 for LM Return LS	0.00	already accounted for		
11. LO2 for LOSS Stores	17.73	******	output of mission	
12. Total Silane @ LSB	11.12	Produced on the Moon, LM suppl LH2		
13. Total LO2 @ LSB reqd	36.08	From LSB Stores, produced on Moon		
14. Total RCS @ LSB reqd	0.42	incl. descent flight needs.		

Notes: Inert Mass = 1250 + 15 % Wp + 2% Lndg. Wt.
Vent & Transfer Losses = Zero (assumption)
Tank Mass = 15% H2, 3.5% O2

NO lunar orbit servicing req'd.

LUNAR RESEARCH CENTER SUPPORT

SILANE FUEL   ORBIT TRANSFER VEHICLE MISSION PERFORMANCE

Case Number: 4414.00 Lunar Module Ascent - Best Case			Oct. 1, 1983
Mission Departure from: Lunar Surface Base			
Mission Destination to: Lunar Orbit Space Sta.		OTV Prop.Req	4.86
Return to Origin on this Mission?	No	OTV B/O Mass	6.36
Mission objective: Deliver Lunar Module to Lunar Orbit Space Station		MPS Eng. Isp	345.00
		O/F Ratio	1.65
Lunar Surface T/W =	7.23	Total Th.,kN	6.74

Mission Sequence Mass History, Tonnes		ΔVelocity Maneauvers Required, meters/sec. MPS	OMS	RCS
1. Departure from LSB	11.29			
2. Ascent Flight	11.29	1889.33		
3. Ascent Orbit	6.45			10.67
4. Terminal Phase	6.43	16.77		9.15
5. Lunar Orbit Spa. Sta	6.36			
6. Total useful Payload	0.00			
7. Crew Module + Crew	0.00			
8. LO2+Tank Payload	0.00			
9. Net LO2 Payload@.965	0.00	LO2 tanks = 0.00 tonnes		
10 LO2 for LM Return LS	0.00	reserved for return w/o P/L (est)		
11. LO2 for LOSS Stores	0.00	****** output of mission		
12. Total Silane @ LSB	1.84	Produced on the Moon, LM suppl LH2		
13. Total LO2 @ LSB reqd	3.03	From LSB Stores, produced on Moon		
14. Total RCS @ LSB reqd	0.06			

Notes: Inert Mass = 1250 + 15 % Wp + 2% Lndg. Wt.
Vent & Transfer Losses = Zero (assumption)
Tank Mass = 15% H2, 3.5% O2

Vehicle Consumption Ascent				Status of Stores-LOSS *See Note 1					Total	Incl.	Status of Stores-LSB					Total
LO2	SIL	RCS		O2 Tnk	LO2	H2 Tnk	LH2	RCS	LOSS	Silane	O2 Tnk	LO2	H2 Tnk	SIL	RCS	LSB
			Initial Stores	0.00	18.36	3.96	22.46	2.40	47.18	58.30	1.28	577.37	0.00	0.00	6.84	585.49
18.36	11.12	0.54		0.64	17.73	0.00	0.00	1.80	18.37	29.49	0.64	541.28	3.96	168.56	6.30	714.44
18.36	11.12	0.42		0.64	35.46	0.00	0.00	1.68	36.10	47.22	0.64	505.20	3.96	157.43	5.88	667.23
18.36	11.12	0.42		0.64	53.19	0.00	0.00	1.56	53.83	64.95	0.64	469.11	3.96	146.31	5.46	620.02
18.36	11.12	0.42		0.64	70.92	0.00	0.00	1.44	71.56	82.68	0.64	433.03	3.96	135.18	5.04	572.81
18.36	11.12	0.42		0.64	88.65	0.00	0.00	1.32	89.29	100.41	0.64	396.94	3.96	124.06	4.62	525.60
18.36	11.12	0.42		0.64	106.38	0.00	0.00	1.20	107.02	118.14	0.64	360.86	3.96	112.93	4.20	478.39
18.36	11.12	0.42		0.64	124.11	0.00	0.00	1.08	124.75	135.87	0.64	324.77	3.96	101.81	3.78	431.18
18.36	11.12	0.42		0.64	141.84	0.00	0.00	0.96	142.48	153.60	0.64	288.69	3.96	90.68	3.36	383.97
18.36	11.12	0.42		0.64	159.57	0.00	0.00	0.84	160.21	171.33	0.64	252.60	3.96	79.56	2.94	336.76
18.36	11.12	0.42		0.64	177.30	0.00	0.00	0.72	177.94	189.06	0.64	216.52	3.96	68.43	2.52	289.55
18.36	11.12	0.42		0.64	195.03	0.00	0.00	0.60	195.67	206.79	0.64	180.43	3.96	57.31	2.10	242.34
18.36	11.12	0.42		0.64	212.76	0.00	0.00	0.48	213.40	224.52	0.64	144.34	3.96	46.19	1.68	195.13
18.36	11.12	0.42		0.64	230.49	0.00	0.00	0.36	231.13	242.25	0.64	108.26	3.96	35.06	1.26	147.92
18.36	11.12	0.42		0.64	248.22	0.00	0.00	0.24	248.86	259.98	0.64	72.17	3.96	23.94	0.84	100.71
18.36	11.12	0.42		0.64	265.95	0.00	0.00	0.12	266.59	277.71	0.64	36.09	3.96	12.81	0.42	53.50
18.36	11.12	0.42		0.64	283.68	0.00	0.00	0.00	284.32	295.44	0.64	0.00	3.96	1.69	0.00	6.29

			Totals
293.69	177.99	6.84	510.40

Total liquid Oxygen gained = 265.32
1000's 0.27

Total liquid Hydrogen + tanks used= 26.42
Ratio, LO S/S Gains/Losses = 7.07 w/Sil. 10.04 wo/Sil
Note 1:LOSS must have 11.12 tonnes of Silane to begin

.D1/LOMBS Lunar Module Operations

8/8/83

Wp Cap. 29.48
SIL Cap 11.12 SILANE FUEL- PRODUCED ON THE MOON Pressure-fed Stage
LO2 Cap 18.36

	Delivery -Tonnes - Descent						Delivery - Tonnes - Ascent						Vehicle Consumption Descent		
	O2 Tnk	LO2	H2 Tnk	LH2	Other		O2 Tnk	LO2	H2 Tnk	LH2	Other		LO2	SIL	RCS
Flt.No.															
1.00	0.00	0.00	3.96	22.46	0.00		0.64	17.73	0.00	0.00	0.00		18.36	11.12	0.60
2.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
3.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
4.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
5.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
6.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
7.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
8.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
9.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
10.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
11.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
12.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
13.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
14.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
15.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
16.00	0.64	0.00	0.00	0.00	0.00		0.64	17.73	0.00	0.00	0.00		0.00	0.00	0.12
						Totals						Totals			
TOTALS:	9.60	0.00	3.96	22.46	0.00	36.02	10.24	283.68	0.00	0.00	0.00	293.92	18.36	11.12	2.40
						1000's		0.28			1000's	0.29			

UTILITY OF OXYGEN/SILANE BIPROPELLANT COMBINATION

FOR USE IN A

LUNAR-BASED PROPULSION SYSTEM

SEPTEMBER 20, 1983

IN-SPACE PROPULSION LIMITED

SACRAMENTO, CALIFORNIA

Appendix B

TABLE OF CONTENTS

I. INTRODUCTION AND SUMMARY

The potential utility of the oxygen/silane bipropellant combination for use in a lunar-based propulsive system and the potential for the on-site manufacture of lunar oxygen and silane are considered in this report. Two tasks are addressed.

Task 1. Feasibility of Oxygen/Silane, O_2/SiH_4, Bipropellant Combination for Rocket Propulsion

Task 2. Feasibility of Production of Silane, SiH_4, from Lunar Materials

Under Task 1, it was found that the propellant properties of O_2 and SiH_4 are more than adequate to support the development of candidate propulsion systems. In addition,

- o Propulsion systems should be developed around the optimum performance mixture ratio, 1.50 to 1.80, rather than minimum fuel mixture ratio, 3.0 to 4.0.
- o Estimated delivered performance for the propulsion system is 340 to 350 sec.
- o Ignition and shutdown characteristics of the engine should not pose special design problems.
- o A pressure-fed engine, in the STS Orbiter OMS Engine format, is recommended as the primary candidate for adequate performance and life.
- o An expander-cycle, pump-fed engine may offer higher performance than a pressure-fed engine and is worthy of detailed study.
- o The presence of $SiO_2(L)$ as a combustion product will affect engine design. The engine exhaust will contain $SiO_2(S)$ and $SiO_2(L)$.
- o Silane is stable and storable in space and lunar environments with properties compatible with those of liquid oxygen.
- o Penalties normally associated with pressure-fed propulsion systems may be minimized in the lunar environment. A pressure-fed propulsion system may prove to be quite competitive with a pump-fed system.

Under Task 2, it appears that silane and oxygen can be produced from lunar mare basalt materials in an integrated facility. In addition,

- o The carbothermal process uses common lunar materials efficiently and produces propellant oxygen and silane precursors with minimum terrestrial resupply.

- o The production of silane from lunar materials may require a key lunar-produced intermediate, magnesium silicide. Mineral acid terrestrial resupply will be required to produce silane by this synthesis.

II. TASK 1. FEASIBILITY OF OXYGEN/SILANE, O_2/SiH_4, BIPROPELLANT COMBINATION FOR ROCKET PROPULSION

A. Physical Chemcial and Propellant Properties of Oxygen and Silane

1. Oxygen

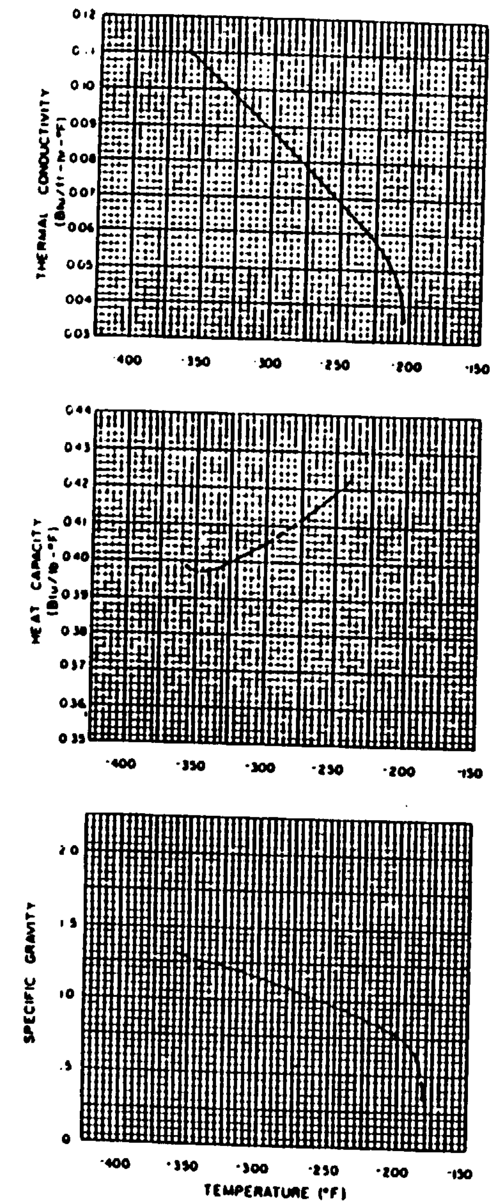
Oxygen, O_2, is a fully flight qualified propellant in both its liquid and gaseous states. There is every reason to believe that it would perform satisfactorily as the oxidizer in GOX/SiH_4 and LOX/SiH_4 bipropellant propulsion systems.

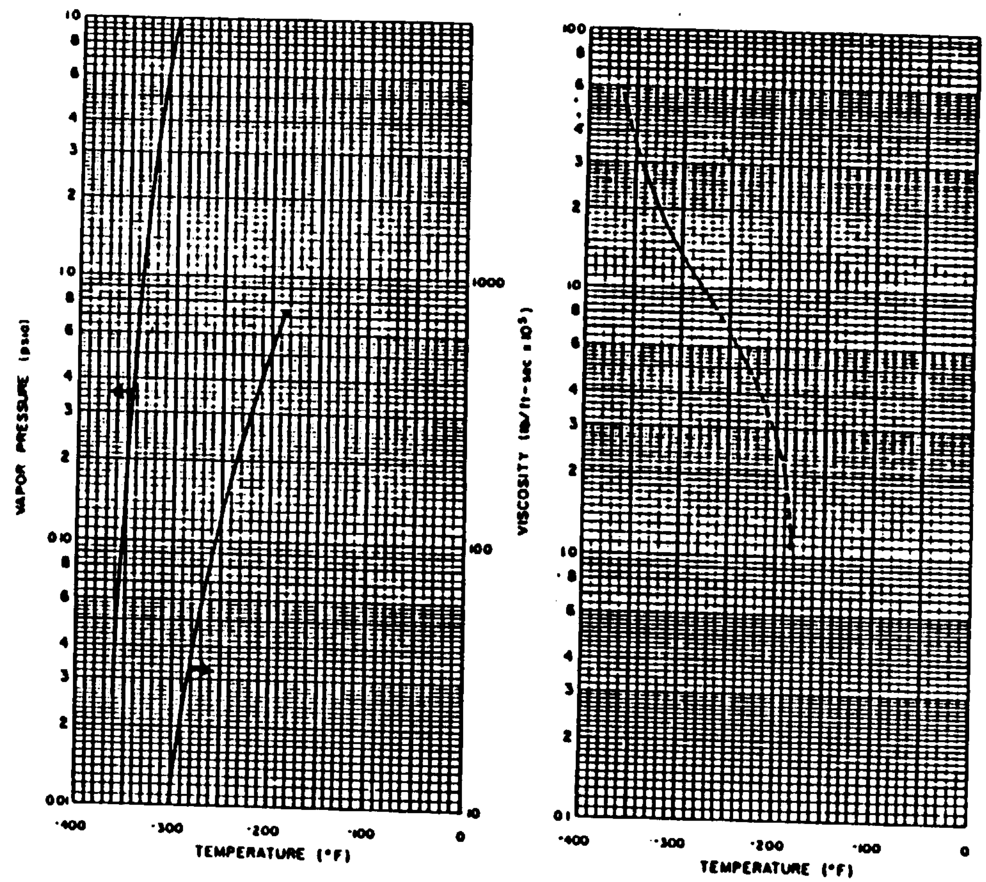
The physical properties of O_2 are presented in Figure 1. The propellant is categorized as a deep cryogenic, e.g., its critical temperature is -182.0°F and its normal boiling point is -247°F (specific gravity, 1.14). It is an agressive oxidizer and combines with all elements except the inert gases of the argon group. Its propellant properties are well characterized. As such, they are not discussed in this report.

2. Silane

The simplest covalent compounds of silicon are the hydrides and the simplest hydride is silane, SiH_4. The higher hydrides, disilane, Si_2H_6, trisilane, Si_3H_8 and so forth, form an homologous series that bears a structural resemblances to the methane series of saturated hydrocarbons. The length of the silicon chain appears to be limited by an inherent instability unknown in carbon chains. The higher hydrides are unstable and the highest member of the series thus far reported is hexasilane, Si_6H_{14} (Reference 1).

Silane is quite stable thermally, being decomposed to silicon and hydrogen only at red heat. The higher hydrides decompose at progressively lower temperatures, e.g., silane dissociates at approximately 800°F, while hexasilane decomposes quite completely at room temperature over a period of several months. The higher hydrides do not break down to elementary hydrogen and silicon as does SiH_4. Rather, they undergo a series of complicated rearrangements resulting in mixtures of simple gaseous hydrides and solid unsaturated hydrides (Reference 1).





PHYSICAL PROPERTIES OF OXYGEN - O_2

MOLECULAR WEIGHT	32.000
FREEZING TEMPERATURE (°F)	-362
NORMAL BOILING POINT (°F)	-297
CRITICAL TEMPERATURE (°F)	-182.0
CRITICAL PRESSURE (psia)	730.6
HEAT OF FORMATION (cal / mole liq@nbp)	-2896
HEAT OF VAPORIZATION (Btu / lb)	91.62

REFERENCE DATA ————
EXTRAPOLATED DATA - - - - - -
CRITICAL POINT •

Figure 1

Of particular importance from the standpoint of possible use of SiH_4 as a fuel is the susceptibility of the hydrides to oxidation. All of the hydrides are extremely sensitive to oxygen and will ignite in air. The reaction proceeds with an explosive puff, evidently because hydrogen is a preliminary product, i.e.,

$$2\ SiH_4 + O_2 = H_2SiO + 2\ H_2.$$

The hydrogen liberated by this initial oxidation forms an explosive mixture with oxygen that is detonated by the rapidly rising temperatures of the system.

The normal hydrides exhibit a physical resemblance to their organic counterparts, as shown by the constant ratio of absolute boiling points, Table 1.

TABLE 1

BOILING POINTS OF HYDRIDES OF SILICON AND CARBON

Hydride	Normal Boiling Points °F	°C	°K	a/b Ratio
SiH_4	-169.4	-111.9	161 (a)	1.44
CH_4	-258.3	-161.3	112 (b)	
Si_2H_6	5.9	- 14.5	259 (a)	1.40
C_2H_6	-127.7	- 88.7	185 (b)	
Si_3H_8	127.2	52.9	326 (a)	1.42
C_3H_8	- 48.1	- 44.5	229 (b)	
Si_4H_{10}	ca.228.2	ca.109	382 (a)	1.39
C_4H_{10}	32.9	0.5	274 (b)	

Additional comparitive physical properties are presented in Table 2.

TABLE 2

PHYSICAL PROPERTIES OF HYDRIDES OF SILICON AND CARBON

Hydride	Melting Point °F	Melting Point °C	Boiling Point °F	Boiling Point °C	Specific Gravity (liquid)
SiH_4	-301	-185	-169.4	-111.9	0.68 @ -185°C
CH_4	-296.7	-182.6	-258.3	-161.3	0.46 @ -182°C
Si_2H_6	-206.5	-132.5	5.9	-14.5	0.69 @ -25°C
C_2H_6	-277.6	-172	-127.2	-88.7	0.546 @ -88°C
Si_3H_8	-178.6	-117	127.2	52.9	0.743 @ 0°C
C_3H_8	-304.8	-187.1	- 48.1	-44.5	0.585 @ -44.5°C
Si_4H_{10}	-130	-90	ca. 228	ca. 109	0.825 @ 0°C
C_4H_{10}	-211	-135	32.9	0.5	0.60 @ 0°C

Although the propellant properties of SiH_4 have not been determined rigorously, it is reasonable to expect them to be similar to those of the light hydrocarbons with the notable exception of ignition characteristics, i.e., the ignition of the O_2/SiH_4 combination should be more easily accomplished than O_2/CH_4 and O_2/C_2H_6.* Therefore, it is instructive to note some additional physical properties of the light hydrocarbons, Table 3 and Figure 2.

*Similarly, the ignition of O_2/SiH_4 should be more easily accomplished than O_2/H_2. As in almost all systems, a modest OX-lead is indicated, e.g., 10 msec. An OX-lag on shut down is indicated as well

TABLE 3

SOME PROPERTIES OF LIGHT HYDROCARBONS

Hydrocarbon	Molecular Weight (g)	Critical Temperature (°F)	Critical Pressure (psia)	Auto Decomposition Temperature (°F)
Methane, CH_4	16	-117	673	1405
Ethane, C_2H_6	30	90	708	1255
Propane, C_3H_8	44	206	617	860
Butane, C_4H_{10}	58	306	551	
(Silane, SiH_4)	32			_ca_. 800

Silane should be categorized as a soft cryogenic, i.e., it is a space storable propellant. Its handling characteristics and stability should be similar to those of the light hydrocarbons with the notable exception of ignition with oxygen, as discussed previously, and toxicity. The comparative physical properties of O_2 (m.p., -362°F, n.b.p., -297°F) and SiH_4 (m.p., -301°F, n.b.p. -182.6°F) should permit adequate flexibility in propulsion system design as SiH_4 is a liquid at the normal boiling point of O_2. The viscosity/temperature relationship of SiH_4(L) will affect the design.

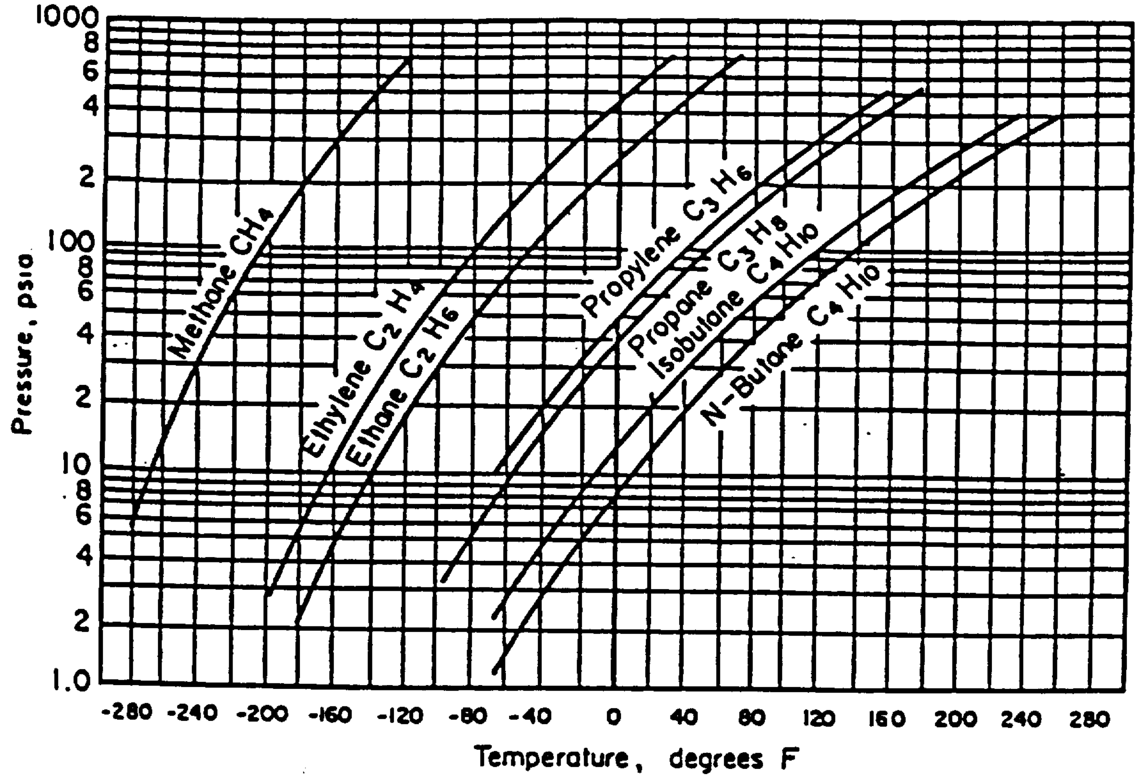


FIG. 2 Vapor pressures of pure hydrocarbons

B. Combustion and Performance Characteristics of Oxygen/ Silane Bipropellant Combination

1. Oxygen/Hydrocarbon Bipropellant Combinations

Before addressing the combustion and performance characteristics of the O_2/SiH_4 bipropellant combination, it is instructive to consider some O_2/Hydrocarbon bipropellant combinations. As indicated in Table 4, O_2/CH_4 offers the highest specific impulse performance. Note, however that the estimated delivered specific impulse varies only ± 3 sec. (± 0.83%) among the light hydrocarbons, while the companion density specific impulse varies ± 16.5 sec (± 2.8%).

TABLE 4

DELIVERED PERFORMANC EOF LOX/HC BIPROPELLANT COMBINATIONS

Bipropellant Combination	Estimated Delivered Vacuum Specific Impulse[a] (lbf-sec/lbm)	Vacuum Density Impulse ($\rho \cdot Ispv$)	Maximum Performance Mixture Ratio ($\dot{W}ox/\dot{W}fu$)	Stoichio-metric Mixture Ratio ($\dot{W}ok/\dot{W}fu$)
LOX/CH_4	360	293	3.25	4.00
LOX/C_2H_6	357	319	2.95	3.72
LOX/C_3H_8	355	323	2.85	3.64
LOX/C_4H_{10}	354	326	2.80	3.57
LOX/RP-1	345	352	2.75	-

[a] Chamber Pressure, 400 psia; Area Ratio, 125:1

All of the exhaust species predicted for the LOX/HC bipropellant combinations by the standard JANNAF methods are gaseous, i.e., the major species are carbon monoxide, hydrogen, water vapor, and carbon dioxide. However, it is important to remember that these combinations do not follow the theoretical predicted combustion combinations chemistry completely, i.e., all of these combinations form some solid carbon as a combustion product. Carbon formation manifests itself as deposits which complicate engine design and operation, particularly turbopumps and combustion chambers.

2. Oxygen/Silane Bipropellant Combination

Some theoretical performance calculations have been made for the O_2/SiH_4 bipropellant combination, e.g.; Table 5 (Reference 2). The impulse is in the same range as the O_2/Hydrocarbon combinations. Note that the cases reported in Table 5 are not for the maximum performance mixture ratio point in an effort to minimize the amount of fuel required for the propulsion system. This has important ramifications for the propulsion system and engine designers as the specific impulse is lower, the combustion temperature is higher, a significant amount of oxygen is present in the combustion chamber, and the amount of fuel available for cooling the combustion chamber is lower. These trends greatly increase the designer's problems.

In addition, most of the Si is present as $SiO_2(L)$ rather than $SiO_2(G)$. This impacts turbopump and combustion chamber design, e.g., turbine life and gas side heat transfer, respectively. The non-equilibrium formation of Si (psuedo-coking) may complicate matters further.

C. Design Considerations for an Oxygen/Silane Bipropellant Engine

1. Propellants

There is every reason to believe that O_2 and SiH_4 will prove to be satisfactory propellants for this propulsion system and its engine. Both propellants have tractable physical, chemical and handling characteristics. There is a reasonable expectation that they are hypergolic and the required ignition will be achieved without difficulty with proper design.

Silane appears to possess the requisite stability to function as a regenerative fuel coolant and as a fuel film coolant, provided it can be produced in high purity. The potential of using oxygen as a regenerative oxidizer coolant exists but this approach is controversial. Note however, that operation at higher mixture ratios, e.g., 3.0 to 4.0, may require regenerative cooling with O_2 as there may not be sufficient SiH_4 to cool the thrust chamber.

TABLE 5

THEORETICAL PERFORMANCE OF LOX/SILANE BIPROPELLANT COMBINATION

Equilibrium Composition

P_C = 147.0 psia
MR = 3.0

Parameter	Chamber	Throat	Exit	Exit
P_C/P	1.0000	1.7113	882.22	5446.0
P, atm	10.003	5.8452	0.0113	0.0018
T, °K	3379	3273	2394	2215
Ae/At		1.0000	100.00	500.00
Ispv, sec.		196.3	340.7	366.9

Pc = 1470.0 psia
MR = 3.0

Pc/P	1.0000	1.7177	913.48	5686.8
P, atm	100.03	58.234	0.1094	0.0176
T, °K	3860	3718	2594	2371
Ae/At		1.000	100.00	500.00
Ispv, sec.		203.9	350.8	376.9

Mole Frations: P_C = 147.0 psia, MR = 3.0

(Major Species)

Species	Chamber	Throat	Exit	Exit
H	0.0228	0.0226	0.0202	0.0187
H_2	0.0284	0.0281	0.0237	0.0217
H_2O	0.3252	0.3301	0.3913	0.4072
O	0.0539	0.0521	0.0350	0.0302
OH	0.1152	0.1101	0.0622	0.0513
O_2	0.2426	0.2425	0.2412	0.2389
SiO	0.1299	0.1227	0.0504	0.0335
SiO_2(L)	0.0597	0.0704	0.1725	0.1954
SiO_2	0.0219	0.0198	0.0051	0.0031

2. Mixture Ratio

Although the desire to operate an engine at higher mixture ratio may be attractive to minimize fuel production requirements and maximize density specific impulse, it is particularly unattractive from the standpoint of engine design. The development of a long-life reusable engine that operates at a throat temperature of 3273°K (5432°F) and an oxygen concentration of 24.25 mole% would be an extremely formidable task, Table 6.

It would be much more reasonable to approach the design of the engine based on the maximum specific impulse performance mixture ratio. In the absence of additional theoretical performance data, this mixture ratio is estimated to be 1.65. This would lower the thrust chamber temperatures, eliminate oxygen as a major combustion species, and provide more fuel for cooling, in addition to increasing the delivered specific impulse.

3. Pump-Fed Engine

Pump-fed liquid bipropellant engines are attractive because they offer higher performance (P_c/P) and lighter weight (smaller) than their pressure-fed counter parts. In addition, they offer lighter weight propulsion systems since thin-wall propellant tanks may be used.

The presence of $SiO_2(L)$ [and perhaps such non-equilibrium species as $SiO_2(S)$, Si(L) and $SiH_2(S)$] appears to mitigate against the selection of the gas-generator and stage-combustion cycles for the pump-fed engine. The development of suitable turbopumps, e.g. turbine blades, for a long-life, reusable engine would be a challenge as the erosive effects of liquid droplets in the turbine drive gas would be life-limiting.

If an adequate power balance can be achieved, an expander cycle pump-fed engine may be feasible. A single expander cycle analysis must leave ample margin for the limited thermal stability of SiH_4 (as compared to H_2). A dual-expander cycle, in which the thrust chamber would be cooled with O_2 and SiH_4, may be the better choice.

TABLE 6

LOX/SILANE THEORETICAL CHAMBER PERFORMANCE PARAMETERS

Parameter	MR, 3.0 P_c, 147 psia	MR, 3.0 P_c, 1470 psia	MR, 4.0 P_c, 147 psia	MR, 4.0 P_c, 1470 psia
Chamber Temperature, °K	3379	3860	3341	3788
Throat Temperature, °K	3273	3718	3233	3645
Chamber O_2, mole fraction	0.24256	0.22809	0.35084	0.34179
Throat O_2, mole fraction	0.024254	0.22887	0.35233	0.34439
Chamber SiO_2(L), mole fraction	0.05965	0.09215	0.	0.11135
Throat SiO_2(L), mole fraction	0.07041	0.10216	0.	0.12010

The presence of $SiO_2(L)$ in the combustion chamber will reduce the gas-side heat transfer. This, in turn, will make it more difficult to obtain a power balance for very high chamber pressure, i.e., to obtain very high specific impulse performance. Detailed analysis would have to be performed to address these and other issues associated with the selection of an expander cycle pump-fed engine.

4. Pressure-Fed Engine

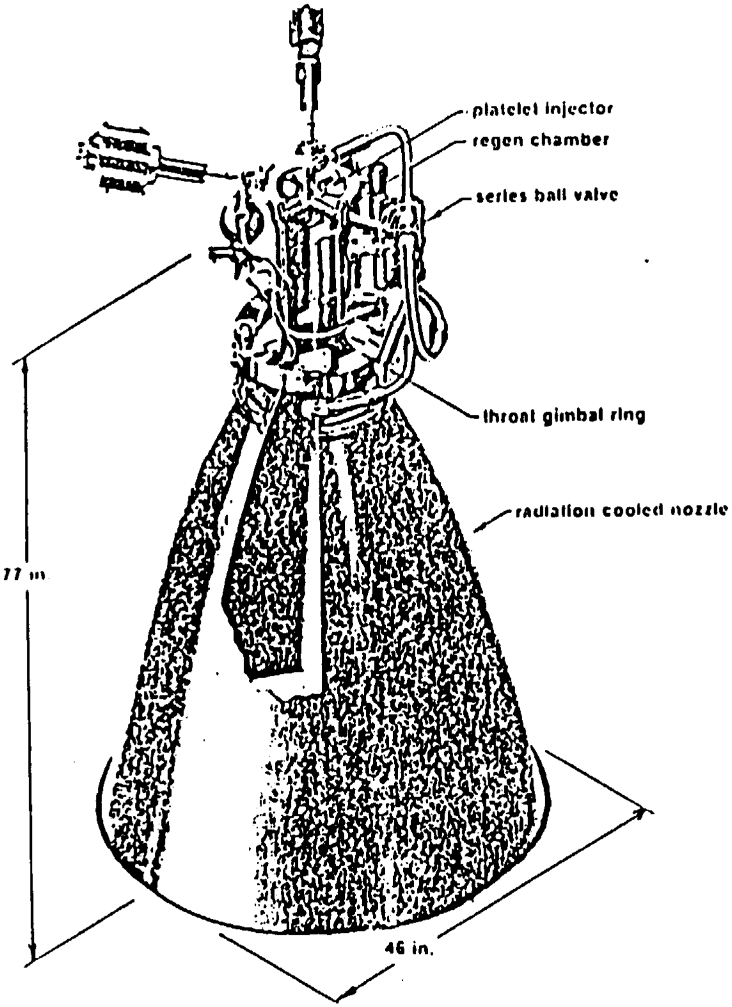
Pressure-fed liquid bipropellant engines are attractive because of their comparative simplicity (no turbopumps). Their disadvantages are lower performance (P_c/P) and the need for heavier weight tanks and a tank pressurization system which results in heavier propulsion systems.

A pressure-fed engine in the STS Orbiter OMS-Engine format would seem to be appropriate for use with the LOX/SiH_4 bipropellant combination (Figure 3). This engine which delivers 6,000-lbf thrust and operates with the nitrogen tetroxide/monomethylhydrazine combination at a mixture ratio of 1.65, has a fuel regeneratively-cooled thrust chamber. OMS-E has a delivered specific impulse performance of 316 sec.

If the regeneratively-cooled thrust chamber can be adequately cooled with silane, and there is every reason to believe it can because of silane's thermal stability and the presence of $SiO_2(L)$ in the thrust chamber, the development of a suitable long-life, reusable engine based on LOX/SiH_4 appears to be quite achievable. Such an engine should have a delivered specific impulse performance in the 340 to 350 sec range.

Finally, a fuel film-cooled engine can be considered as a work-around design should the development of a regeneratively-cooled engine prove to be unworkable. The engine would be lighter but its delivered specific impulse would be lower, perhaps as much as 20 sec.

The pressure-fed propulsion system penalties associated with earth-launched systems would have to be reconsidered in the light of a moon-launched system. In the 1/6 g environment of the moon, the apparent disadvantages of a pressure-fed system may be less and a pressure-fed engine operating at higher chamber pressure may be appropriate. Detailed analysis would have



parameter	value
thrust, lbf	6000
mixture ratio	1.65
chamber pressure, psia	125
specific impulse, lb sec/lb	316
propellants	N_2O_4/MMH
total flowrate, lb/sec	19
inlet temperature, °F	40 to 100
single burn duration, sec	1250 *
cumulative firing life, sec	54000
regen. exit area ratio	6:1
area ratio	55:1
weight (dry), lbm	260
storage life, yrs	10
restarts	unlimited
blowdown, lbF	7,600 to 5,500
inlet oxid. pressure, psia	239
inlet fuel pressure, psia	242

Figure 3 . space shuttle OMS engine

to be performed to address these and other issues associated with the selection of a pressure-fed propulsion system.

III. TASK 2. FEASIBILITY OF PRODUCTION OF SILANE, SiH_4 FROM LUNAR MATERIALS

A. Lunar Minerals

The mineralogy of lunar materials is dominated by five minerals: pyroxenes, olivines, plagioclase feldspars, ilmenite, and spinel. A host of other minerals have been reported from analyses of lunar samples; they are listed in Table 2-I. The mineral chemistries are presented in more detail in the subsections that follow; however, the following overview will be helpful.

Pyroxene—The basic chemistry of the pyroxenes can be represented by a mixing of the end member minerals: enstatite ($MgSiO_3$), wollastonite ($CaSiO_3$), and ferrosilite ($FeSiO_3$).[1] These are usually abbreviated as En, Wo, and Fs, respectively. There are three structural forms: orthopyroxene, pigeonite (or low-calcium clinopyroxene), and augite (or high-calcium clinopyroxene); they are chemically differentiated by their $CaSiO_3$ content—orthopyroxene lowest and augite highest. All forms have a wide range of enstatite and ferrosilite contents. The minerals accept large amounts of Al (up to 12 percent Al_2O_3), Ti (up to 5 percent TiO_2), Mn (up to 0.5 percent MnO), Cr (up to 1.25 percent Cr_2O_3), and Na (up to 0.2 percent Na_2O) into solid solution. An average chemistry cannot be defined easily.

Olivine—The basic chemistry of the olivines is represented by a solid solution of forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4), represented as Fo and Fa. The mineral accepts limited amounts of Ca, Cr, Ti, and Al into solution. There are several ranges of compositions—most are between Fo_{75} and Fo_{50}.

Feldspar—Lunar plagioclase feldspars are solid solutions of anorthite ($CaAl_2Si_2O_8$) and albite ($NaAlSi_3O_8$), An and Ab, respectively. They can contain up to 2 mole percent of orthoclase ($KAlSi_3O_8$).

Ilmenite—Lunar ilmenites are mixtures of ilmenite ($FeTiO_3$) with small amounts of geikielite ($MgTiO_3$). They have a varied minor element chemistry.

Spinel—Spinel minerals are complex mixtures of ulvöspinel (Fe_2TiO_4), chromite ($FeCr_2O_4$), hercynite ($FeAl_2O_4$), picrochromite ($MgCr_2O_4$), spinel ($MgAl_2O_4$), and magnesium-titanate (Mg_2TiO_4). Their chemistries are complex and varied with substitutions of many minor and trace elements reported.

In subsequent portions of this report, some of the [illegible] chemical properties of minerals and some other materials are summarized. These data represent a simplified and condensed form of information that can be found in the "Handbook of Physical Constants," S. P. Clark, Jr., editor,

[1] Compositions of this and other minerals are often reported as mole percent of end member minerals, written as $Wo_2En_{80}Fs_{18}$, for example.

Table 2-1.—Lunar Minerals

Major minerals, while variable in abundance, are known to occur in concentrations up to 100 percent. Minor minerals generally occur at less than 2 percent, although some, particularly ilmenite, achieve abundances of 10 percent. Trace minerals never exceed a few tenths of a percent and some are reported only as isolated single grains. Those marked with question marks are controversial with respect to indigenous lunar origin.

Major

Olivine $(Mg,Fe)_2SiO_4$
Pyroxene $(Ca,Mg,Fe)SiO_3$
Plagioclase feldspars
  $(Ca,Na)\,Al_2Si_2O_8$

Minor

Spinels $(Fe,Mg,Al,Cr,Ti)O_4$
Armalcolite (Fe_2TiO_5)
Silica (quartz, tridymite,
  cristobalite) SiO_2
Iron Fe (variable amounts of Ni
  and Co)
Troilite FeS
Ilmenite $FeTiO_3$

Trace

Phosphates

Apatite[a] $Ca_5(PO_4)_3(F,Cl)_3$
Whitlockite[a] $Ca_9(Mg,Fe)(PO_4)_7(F,Cl)$

Zr mineral

Zircon[a] $ZrSiO_4$
Baddeleyite ZrO_4

Silicates

Pyroxferroite $(Fe,Mg,Ca)SiO_3$
Amphibole $(Ca,Mg,Fe)(Si,Al)_8O_{22}F$
Garnet(?)
Tranquilletyite[a] $Fe_8Zr_2Ti_3Si_3O_4$

Sulfides

Mackinawite $(Fe,Ni)_9S_8$
Pentlandite $(Fe,Ni)_9S_8$
Cubanite $CuFe_2S_3$
Chalcopyrite $CuFeS_2$
Sphalerite $(Zn,Fe)S$

Oxides

Rutile TiO_2
Corrundum(?) Al_2O_3
Hematite(?) Fe_2O_3
Magnetite Fe_3O_4
Goethite(?) $FeO(OH)$

Metals

Copper(?) Cu
Brass(?)
Tin(?) Sn

Zr-rich mineral

Zirkilite or zirconolite[a] $CuZrTi_2O_7$

Meteoritic minerals

Schreibernite $(Fe,Ni)_3P$
Cohenite $(Fe,Ni,Co)_3C$
Niningerite $(Mg,Fe,Mn)S$
Lawrencite(?) $(Fe,Ni)Cl_2$

[a]These minerals are known to exhibit complex substitutions, particularly of elements like Y, Nb, Hf, U, and the rare earth elements that are concentrated in these minerals.

published by the Geological Society of America (1966), and in "Thermodynamic Properties of Minerals and Related Substances at 298.15 K and One Bar (10^5 Pascals) Pressure and at Higher Temperatures," U.S. Geological Survey, by R.A. Robie, B.S. Hemingway, and J.R. Fisher. These data are always referenced to the stable form of the materials or elements at the cited temperature and at 10^5 N/m^2.

Finally, the mineralogical data presented here are highly abstracted. More complete data are available in "Rock Forming Minerals", five volumes by W.A. Deer, R.A. Howie, and J. Zussman, published by John Wiley and Sons, Inc.

The minerals of the moon are not uniformly distributed. For example:

Chemical differences between the maria and the highlands were demonstrated by the orbiting X-ray fluoresence experiment. Data from one orbit each of Apollo 15 and 16 are shown in Figure 1-3. The maria have consistently lower aluminum/silicon (Al/Si) ratio. The major variations of the Al/Si ratio are consistent with the mafic basalts returned from the mare (lower Al/Si) and the anorthositic rocks of the highlands (higher Al/Si). (Reference 3)

The chemistry of the lunar minerals will be an important influence on the site location of permanent bases and production facilities.

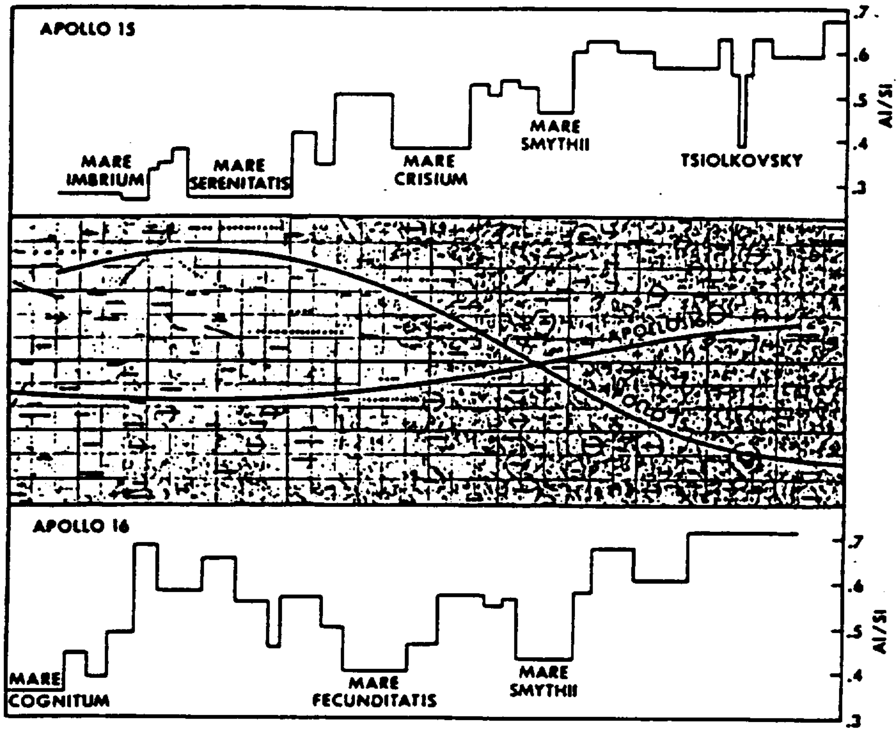


FIGURE 1-3.—Data from the X-ray fluorescent experiment that orbited the Moon during Apollo 15 and 16. The map shows one typical orbit from each mission. The top and bottom graphs show changes in the ratio of Al to Si. Low values are consistent with the feldspar-poor mare regions; high values are consistent with the feldspar-rich highlands.

1. Pyroxenes

Pyroxenes are mixtures of the minerals enstatite ($MgSiO_3$), wollastonite ($CaSiO_3$), and ferrosilite ($FeSiO_3$), abbreviated En, Wo, and Fs respectively. There are three structural forms: orthopyroxene, pigeonite (low-calcium clinopyroxene), and augite (high-calcium clinopyroxene). All forms have a wide range of enstatite and ferrosilite contents and accept large amounts of Al (up to 12 percent Al_2O_3), Ti (up to 5 percent TiO_2), Mn (up to 0.5 percent MnO), Cr (up to 1.25 percent Cr_2O_3), and Na (up to 0.2 percent Na_2O) into solid solution. Average chemistry is not easily defined. The occurrence of pyroxene on the lunar surface is shown in table 2-II, and two analyses of typical pyroxenes are given in table 2-III.

Pyroxenes are potential ores for silicon, calcium, magnesium, oxygen, and possibly aluminum and iron. Based upon the occurrence shown in Table 2-II, mare basalts may be considered ores for lunar pyroxenes.

TABLE 2-II.—Abundance of Lunar Pyroxene

Lunar material	*Percent pyroxene, vol.%*	*Comments*
Mare basalts	40 to 65	A few samples contain less pyroxene (as low as 30 percent in some cases and down to 5 percent in one vitrophyre).
Anorthositic rocks	0 to 40	Pyroxene in these rocks is mostly Ca-poor.
Fragmental breccias	5 to 30	The quoted value is for mineral grains more than 25 micrometers across.
Soils	5 to 20	The pyroxene composition and amount resembles that of the local rocks. Pyroxene is high-Ca in mare regions and low-Ca in highland regions.

TABLE 2-III.—Analyses of Typical Lunar Pyroxenes

Compound	*Mare, wt.%*	*Highland, wt.%*
SiO_2	47.84	53.53
TiO_2	3.46	.90
Cr_2O_3	.80	.50
Al_2O_3	4.90	.99
FeO	8.97	15.42
MnO	.25	.19
MgO	14.88	26.36
CaO	18.56	2.43
Na_2O	.07	.06
Total	99.73	100.39

2. Olivine

Olivine is one of the dominant lunar minerals. It is a solid solution of forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4), with most compositions between Fo_{75} and Fo_{50} (75 to 50 mole percent forsterite). The occurrence of olivine on the Moon is shown in Table 2-IV, and two analyses of typical lunar olivines are given in Table 2-V.

Olivine is a potential source of magnesium, iron, silicon, and oxygen. Based on the occurrence shown in Table 2-IV, mare basalts may be considered ores for this mineral.

TABLE 2-IV.—Abundance of Lunar Olivine

Lunar material	*Percent olivine, vol.%*	*Comments*
Mare basalts	0 to 35	The olivine content is a function of the detailed chemistry of each mare lava flow.
Anorthositic rocks	0 to 40	Most anorthositic rocks contain only a few percent olivine. Rocks with up to 40 percent olivine are rare. One very rare rock contains 99 percent olivine.
Fragmental breccias	0 to 5	Olivine content is a function of the local rocks. It is higher in regions where local rocks contain olivine.
Crystalline breccias	1 to 5	Olivine in these rocks are usually clasts greater than 50 micrometers across.
Soil	0 to 4	The olivine content is a function of the local rocks.

TABLE 2-V.—Analyses of Typical Lunar Olivine

Compound	*Mare, wt.%*	*Highland, wt.%*
SiO_2	37.36	37.66
TiO_2	.11	.09
Cr_2O_3	.20	.15
Al_2O_3	<.01	.02
FeO	27.00	26.24
MnO	.22	.32
MgO	35.80	35.76
CaO	.27	.16
	<.01	<.01
Total	100.97	100.40

3. Plagioclase Feldspar

Plagioclase feldspar is one of the dominant groups of lunar minerals and occurs in all natural materials found on the lunar surface. The occurrence of plagioclase in lunar materials is given in table 2-VI, and two analyses of lunar plagioclase are given in table 2-VII.

Most lunar feldspars have anorthite contents greater than An_{80}. The mineral anorthite ($CaAl_2Si_2O_8$) is a potential source of aluminum, silicate, silicon, and oxygen—all of which are required for fabrication of structures in space. Based on the known occurrence of plagioclase (table 2-VI), regions of light-matrix breccia may be considered potential ores for lunar plagioclase.

TABLE 2-VI.—Abundance of Plagioclase in Lunar Materials

Lunar material	*Percent plagioclase, vol.%*	*Comments*
Mare basalts	15 to 35	The plagioclase abundance is approximately the same in both high-Ti and low-Ti mare basalts.
Anorthositic rocks	40 to 98	Most anorthositic rocks contain more than 75 percent plagioclase; anorthositic rocks with less than 70 percent plagioclase are rare. Anorthositic rocks are uncommon on the lunar surface and no deposit of anorthositic rocks is known at this time.
Crystalline breccias	50 to 75	These rocks are limited to the lunar highlands.
Vitric breccias	15 to 50	These rocks are very fine grained.
Light-matrix breccias	70 to 90	These rocks are most abundant at North Ray Crater (Apollo 16 site).
Soil	10 to 60	Soils resemble the local bedrock. Thus, soils in mare regions contain little plagioclase whereas soils in highland regions contain more plagioclase.

TABLE 2-VII.—Analyses of Typical Lunar Plagioclase

Compound	*Mare, wt.%*	*Highland, wt.%*
SiO_2	46.06	46.67
TiO_2	.15	.02
Al_2O_3	33.71	33.51
FeO	.68	.25
MnO	.01	—
MgO	.31	.09
CaO	18.07	17.78
BaO	—	<.01
Na_2O	.67	1.51
K_2O	.04	.13
Total	99.70	99.97

4. Ilmenite

Ilmenite is one of the minor lunar minerals, and its abundance is generally less than 2 percent. However, there are areas on the Moon where ilmenite abundance surpasses 10 percent. The occurrence of ilmenite on the Moon is shown in table 2-VIII, and two analyses of typical lunar ilmenite are given in table 2-IX.

The mineral ilmenite ($FeTiO_3$) is a potential source for iron, titanium, and oxygen. Based upon the occurrence of ilmenite (table 2-VIII), high-titanium mare basalts may be considered as potential ores for this mineral.

TABLE 2-VIII.— Abundance of Ilmenite in Lunar Materials

Lunar material	*Percent ilmenite, vol.%*	*Comments*
Mare basalts	0 to 25	Ilmenite abundance is a strong function of basalt type. High-Ti basalts tend to contain more than 15 percent ilmenite while low-Ti basalts tend to contain less than 10 percent. Vitrophyres of both high- and low-Ti contents contain less than 1 percent.
Anorthositic rocks	trace	Almost no ilmenite occurs in these rocks.
Fragmental breccias	2 to 12	These values are for ilmenite grains larger than 25 micrometers across. The ilmenite content of a breccia resembles the local terrain. In high-Ti mare regions the value is approximately 10 percent, in low-Ti mare regions it is approximately 4 percent and in the highlands it is approximately 1 percent.
Crystalline breccias	1 to 2	These rocks are limited to highland regions. The ilmenite is generally approximately one micrometer across.
Soil	0.5 to 5	The ilmenite content is a function of local rocks. It is high in regions where local rocks are high in ilmenite content and vice versa.

TABLE 2-IX.— Analyses of Typical Lunar Ilmenite

Compound	*Mare, wt.%*	*Highland, wt.%*
SiO_2	0.01	0.21
TiO_2	53.58	54.16
Cr_2O_3	1.08	.44
Al_2O_3	.07	<.01
FeO	44.88	37.38
MnO	.40	.46
MgO	2.04	6.56
ZrO	.08	.01
V_2O_3	.01	<.01
Nb_2O_5	<.01	.13
Total	102.16	99.37

B. LUNAR MATERIALS

Lunar materials may be classified as follows: (1) regolith, a fine-grain deposit loosely referred to as "lunar soil"; (2) igneous rocks that were derived from the Moon's interior by well-known igneous processes; and (3) breccias which represent lunar deposits that were lithified by the effects of meteorite impact. Data on these types of lunar material are given in this section.

1. Regolith

The relatively young basalt surfaces inside the large mare basins are dominated by craters less than 1 kilometer in diameter and are particularly influenced by the cumulative bombardment of meteoroids. This bombardment resulted in the fine-grain deposit known as "regolith" and more loosely referred to as "lunar soil." The lunar highland, though not dominated by these small craters, also has a regolith resulting from meteoroid bombardment.

Because of the numerous impacts in the regolith, it is highly comminuted and very rich in glass. Descriptions of the regolith are given here in terms of grain size, chemistry, and mineralogical constituents.

Physical properties of the lunar regolith are known with a high degree of confidence. Unfortunately, however, direct sampling was limited to a maximum depth of approximately 3 meters. In addition, data from geophysical experiments (such as the active seismic, traverse gravimeter, and surface electrical experiments) have not permitted unambiguous interpretation of soil thickness or depth to rock. Deep drill holes and a more definitive geophysical program will be required to characterize the subsurface physical properties.

Quantitative measurements of the regolith thickness are given in Table 3-I; they are very few and are essentially confined to the Apollo landing sites.

TABLE 3-I.—Mean Regolith Thickness

Location	Photogeology, m	Seismometer, m
Flamsteed Ring	3.3	—
NE of Wichmann Crater	3.3	—
Apollo 12 site	4.6	3 to 4
Apollo 15 site	~7	5
Apollo 11 site	4.6	3 to 6
SE Mare Tranquillitatis	7.5	—
Apollo 17 site	~8	~8
Apollo 16 site	~8 to 10	12 to 15
Highland Plains	16	—
Apollo 14 site	—	10 to 20

2. Igneous Rocks

a. Mare Basalts:

The mare basalts are igneous rocks derived from the interior of the Moon as liquids by well-known igneous processes. The mare basalts can be divided into two major chemical groups based on titanium dioxide (TiO_2) content: those that have TiO_2 > ≈9.0 weight percent (primarily reported from the Apollo 11 and 17 sites) and those that have TiO_2 <5.0 weight percent. The range of composition for the major oxides in each group is shown in Table 3-VII. In addition to TiO_2, there are significant differences in SiO_2 with the high-titanium basalts (HTB) being 4 to 10 weight percent lower than the low-titanium basalts (LTB). All the other oxides show significant overlap. The LTB's do generally have more MgO and FeO. Analyses of representative lunar samples are shown in Table 3-VIII.

One advantage of this chemical grouping, in addition to the obvious differences, is that these basalt types can be differentiated at a 1-kilometer scale on the Moon from Earth-based spectral studies. Much of the near side of the Moon has already been mapped with respect to distinguishing these two basalt units.

Differences in the chemistry are quite logically reflected in significant differences in the modal mineralogy (based on volume percent of the minerals present) as shown in Table 3-IX. The differences in titanium content are reflected in the much higher content of opaque minerals (ilmenite and armalcolite) in the HTB's. The differences in silica are evident in a corresponding decrease in the relative plagioclase and pyroxene content of the HTB's.

TABLE 3-VII.—Range of Major Element Chemistry

Chemical	*High-Ti basalts (HTB), wt.%*	*Low-Ti basalts (LTB), wt.%*
SiO_2	37.8 to 40.7	43.9 to 48.4
TiO_2	9.6 to 13.4	1.8 to 4.8
Al_2O_3	8.0 to 10.9	7.3 to 10.8
FeO	16.5 to 19.8	19.3 to 22.5
MnO	0.2 to 0.3	0.2 to 0.3
MgO	6.7 to 10.3	6.5 to 16.5
CaO	10.1 to 12.7	8.0 to 11.8
Na_2O	0.3 to 0.5	0.2 to 0.4
K_2O	0.1 to 0.3	0.5 to 0.7
Cr_2O_3	0.3 to 0.6	0.3 to 0.6
P_2O_5	0.1 to 0.2	0.4 to 0.11
S	0.1 to 0.2	0.4 to 0.8

In texture, the two groups are not mutually exclusive. They both show variants from the vitrophyric basalts to coarse-grain ophitic basalts or fine- to medium-grain gabbros. In general, the coarser grain the rock the more friable it is. Some of the most easily disaggregated rocks are the fine- to medium-grain gabbros. Residual glass and crystal shape appear to be the agents primarily responsible for the toughness of the rocks and, where the glass is lacking and the crystals are equant to subequant, the rocks are more friable. Some specimens have micrometer to centimeter scale cavities (vugs and vesicles).

TABLE 3-VIII.—*Chemistry of Mare Basalts*

Chemical	*High-Ti basalts*			*Low-Ti basalts*				
	10003	*10017*	*70215*	*12064*	*12021*	*12009*	*15555*	*15076*
				Weight percent				
SiO_2	39.8	40.6	37.8	46.3	46.7	45.0	44.6	48.4
TiO_2	11.3	11.8	13.0	4.0	3.5	2.9	2.1	1.9
Al_2O_3	10.7	8.0	8.9	10.7	10.8	8.6	8.7	9.0
Cr_2O_3	.3	.4	.4	.4	.4	.6	.6	.3
FeO	19.8	19.7	19.7	19.9	19.3	21.0	22.5	20.3
MnO	.3	.2	.3	.3	.3	.3	.3	.3
MgO	6.9	7.7	8.4	6.5	7.4	11.6	11.4	8.6
CaO	11.1	10.7	10.7	11.8	11.4	9.4	9.4	10.5
Na_2O	.6	.5	.4	.3	.3	.2	.3	.3
K_2O	.06	.3	.05	.07	.07	.06	.04	.07
P_2O_5	.1	.2	.09	.04	.09	.07	.06	.07
S	.18	.22	.18	.07	—	.06	.06	.08
Total	101.14	100.32	99.92	100.38	100.26	99.79	100.06	99.82
				Trace chemicals				
Li ppm	9	18.1	7.1	—	8.37	—	6.36	—
Rb ppm	.49	5.63	.356	—	1.14	—	.445	0.917
Sr ppm	152.7	175	121	—	128	—	84.4	12
Ba ppm	108	309	56.9	—	71.1	—	32.2	62.7
La ppm	14.7	26.6	5.22	6.76	—	6.1	8.06	7.38
Ce ppm	45.5	77.3	16.5	17.5	19.8	16.8	6.26	15.1
Nd ppm	38.3	59.5	16.7	16	14.4	16	2.09	10.6
Sm ppm	14.4	20.9	6.69	5.51	4.84	4.53	.688	3.52
Eu ppm	1.36	2.14	1.37	1.16	1.12	.94	2.9	.978
V ppm	63	46	50	119	—	153	—	135
Sc ppm	74	86	86	63	50	46	—	47
Co ppm	14	31	23	27	28	49	—	41

TABLE 3-VIII.—Concluded

Chemical	High-Ti basalts			Low-Ti basalts				
	10003	10017	70215	12064	12021	12009	15555	15076
				Trace chemicals - concluded				
Gd ppm	19.5	27.4	10.4	7.2	6.59	5.2	2.9	4.95
Dy ppm	21.9	31.7	12.2	9.03	7.86	7.13	3.27	5.60
Er ppm	13.6	20.0	7.4	6	4.53	3.6	1.7	3.40
Yb ppm	13	14.2	7.04	4.59	4.12	3.74	1.45	2.77
Lu ppm	1	2.66	1.03	.67	.64	.55	—	36
Zr ppm	309	476	—	114	—	107	76	—
Hf ppm	11.6	17.9	6.33	3.9	4.1	4	—	2.1
Th ppm	.97	2.97	.34	.84	.95	.88	.46	.59
U ppm	.254	.784	.13	.22	.26	.24	.13	.15
Ir ppb	—	.02	.003	—	—	.08	.006	—
Re ppb	—	—	.0015	—	—	—	.0013	—
Au ppb	—	.72	.026	—	—	—	.139	—
Ni ppm	2.6	60	13	—	—	52	42	11
Sb ppb	—	—	.18	—	—	—	.67	—
Ge ppb	—	—	1.66	—	—	<41	8.5	—
Se ppb	—	215	176	—	—	—	156	—
Te ppb	—	—	2.1	—	—	—	3.4	—
Ag ppb	—	16	1.1	—	—	—	1.0	—
Bi ppb	—	1.15	.099	—	—	—	.089	—
Zn ppm	—	18	2.1	—	—	1.8	.78	—
Cd ppb	—	68	1.8	—	—	2.2	2.1	—
Tl ppb	—	6.16	.16	—	—	—	.20	—

The ranges of mineral compositions are shown in tables 3-IX and 3-X for both the HTB's and LTB's. The differences in mineral compositions between the two basalt types are most significant for the TiO_2 content of the opaques. The higher TiO_2 content in the HTB opaques reflects the presence of armalcolite which is not found in the LTB's.

b. Plutonic Rocks:

Occasional coarse-grain rocks have been returned from the Moon, and their modal data and mineral chemistries are summarized in tables 3-XI and 3-XII. The plagioclase in these rocks is very rich in anorthite (90 to 97 vol.%), the olivine is very rich in forsterite (Fo_{90}), and the pyroxenes are very magnesium-rich (En/Fs > 9). Their chemistries are reported in table 3-XIII. The very plagioclase-rich specimens (15415 and 60025) are discussed as cataclastic anorthosites in the section on breccias.

TABLE 3-IX.—Range of Modal Mineralogy (vol.%)

Composition	High-Ti basalts	Low-Ti basalts
Pyroxene	42 to 60	42 to 70
Olivine	0 to 10	0 to 36
Plagioclase	15 to 33	17 to 33
Opaques	10 to 34	1 to 11
Silica	0 to 6	0 to 5
Mesostasis	0 to 9	0 to 3
Vesicles and holes	0 to 10	0 to 2
Others	0 to 4.	0 to 2

TABLE 3-X.—Ranges of Chemical Compositions for Major Minerals (wt.%)

(a) High-titanium basalts

Chemical	Pyroxene	Olivine	Plagioclase	Opaques
SiO_2	44.1 to 53.8	29.2 to 38.6	46.9 to 53.3	<1.0
Al_2O_3	0.6 to 7.7	—	28.9 to 34.5	0 to 2.0
TiO_2	0.7 to 6.0	—	—	52.1 to 74.0
Cr_2O_3	0 to 1.0	0.1 to 0.2	—	0.4 to 2.2
FeO	8.1 to 45.8	25.4 to 28.8	0.3 to 1.4	14.9 to 45.7
MnO	0 to 0.7	0.2 to 0.3	—	<1.0
MgO	1.7 to 22.8	33.5 to 36.5	0 to 0.3	0.7 to 8.6
CaO	3.7 to 20.7	0.2 to 0.3	14.3 to 18.6	<1.0
Na_2O	0 to 0.2	—	0.7 to 2.7	—
K_2O	—	—	0 to 0.4	—

(b) Low-titanium basalts

Chemical	Pyroxene	Olivine	Plagioclase	Opaques
SiO_2	41.2 to 54.0	33.5 to 38.1	44.4 to 48.2	<1.0
Al_2O_3	0.6 to 11.9	—	32.0 to 35.2	0.1 to 1.2
TiO_2	0.2 to 3.0	—	—	50.7 to 53.9
Cr_2O_3	0 to 1.5	0.3 to 0.7	—	0.2 to 0.8
FeO	13.1 to 45.5	21.1 to 47.2	0.4 to 2.6	44.1 to 46.8
MnO	0 to 0.6	0.1 to 0.4	—	0.3 to 0.5
MgO	0.3 to 26.3	18.5 to 39.2	0.1 to 1.2	0.1 to 2.3
CaO	2.0 to 16.9	0 to 0.3	16.9 to 19.2	<1.0
Na_2O	0 to 0.1	—	0.4 to 1.3	—
K_2O	—	—	0 to 0.3	—

c. Pyroclastic Materials:

Glass spheres are common in the lunar soils. Two peculiar concentrations of these have been found: the green glass (sample 15426) and the orange glass (sample 74220). Their analyses are recorded in Table 3-XIII.

d. Granite Glasses:

Glass fragments have been reported that are very high in SiO_2. Chemistries range up to extremes like the composition shown in the following table.

"Granite" Glass (ref. 3-8)

Chemical	*Weight percent*
SiO_2	73.12
TiO_2	.50
Al_2O_3	12.37
Cr_2O_3	.35
FeO	3.49
MgO	.13
CaO	1.27
Na_2O	.61
K_2O	5.91

It must be emphasized that these glass fragments are rare (<1 percent by weight of material), but are ubiquitous in that some examples are found in almost every soil sample.

TABLE 3-XI.—Modal Mineralogy of Plutonic Rocks (vol.%)

Lunar mineral	*Sample number—*			
	15415	*60025*	*72415*	*76535*
Pyroxene	3	1	3	4 to 5
Plagioclase	97	98 to 99	4	37 to 60
Olivine	—	—	93	35 to 58

TABLE 3-XII.—Mineral Chemistries of Plutonic Rocks (wt.%)

(a) Sample 72415

Chemical	Plagioclase	Low-Ca pyroxene	High-Ca pyroxene	Olivine	Cr-spinel	Metal
SiO_2	44.79	56.05	54.13	40.24	0.04	0.05
TiO_2	<.01	.28	.11	.02	1.05	<.01
Al_2O_3	35.00	.96	1.22	<.01	16.71	—
Cr_2O_3	—	.26	1.11	.04	51.81	.54
MgO	.23	32.29	18.40	47.65	10.60	.01
FeO	.14	6.94	2.71	12.29	19.27	67.65
MnO	—	.15	.11	.13	.58	.02
CaO	19.25	2.24	22.50	.13	—	.01
Na_2O	.62	.01	.05	—	—	—
K_2O	.09	—	—	—	—	—
BaO	.04	—	—	—	—	—
ZrO_2	—	—	—	—	<.01	—
V_2O_3	—	—	—	—	.37	—
Nb_2O_5	—	—	—	—	.05	—
NiO	—	—	—	<.01	—	30.42
Co	—	—	—	—	—	1.42
Total	110.17	99.18	100.34	100.50	100.48	100.13

(b) Sample 76535

Chemical	Plagioclase	Olivine	Low-Ca pyroxene	Low-Ca pyroxene	High-Ca pyroxene	Cr-spinel
SiO_2	44.21	40.30	55.89	56.43	53.48	.14
TiO_2	.03	.01	.42	.27	.53	.78
Cr_2O_3	—	.02	.80	.72	.72	50.72
Al_2O_3	35.89	<.01	1.26	1.07	1.00	16.02
MgO	.07	47.96	32.23	33.47	18.11	9.24
CaO	19.60	.03	1.44	.66	23.44	—
FeO	.10	12.30	7.55	8.14	2.87	20.84
MnO	—	.16	.17	.16	.06	.76
BaO	<.01	—	—	—	—	—
Na_2O	.29	—	.02	.03	.02	—
K_2O	.05	—	—	—	—	—
ZrO_2	—	—	—	—	—	.06
V_2O_3	—	—	—	—	—	.72
Nb_2O_5	—	—	—	—	—	<.01
NiO	—	<.01	—	—	—	—
Total	100.25	100.78	99.78	100.95	100.23	99.29

3. Breccias

Meteorite impact is the dominant process affecting the physical nature of the lunar surface. The loose deposits produced by impacts constitute the regolith. Those deposits that have been lithified (turned into rock) by impact are called breccias.

Breccias display various physical and chemical properties. Physical properties are dependent upon the environment of the deposition, whereas chemical properties reflect the average composition of the surface struck by the meteorite.

Physical properties range from friable rocks with approximately one-third pore space to tough rocks with almost no pore space. Grain sizes may be "well sorted" or "poorly sorted." Pore space may consist of micrometer-size cracks and gashes to millimeter- or centimeter-size holes. Breccias may contain from 0 to 50 percent glass.

Impacts are effective mixers of target materials, and all deposits from a single impact have approximately the same composition. It is also true that all impacts in a given region have approximately the same target composition. Therefore, the breccias in the lunar highlands have compositions similar to the lunar crust, whereas the breccias in the mare plains have compositions similar to mare basalts.

Essentially, every sample returned from the lunar highlands during the Apollo and Luna missions is a breccia. Approximately one-third of the samples returned from the mare plains are breccias, the remainder being basalts.

For this report, the following classification is used to distinguish rocks with different physical and chemical properties:

Physical properties	*Chemical subgroup*
Vitric-matrix	Mare — High Ti Mare — Low Ti KREEP Anorthositic gabbro
Light matrix	
Cataclastic anorthosite	
Crystalline matrix	KREEP Anorthositic gabbro
Granulitic matrix	

Typical members of each group are described in this section. Major, minor, and trace elements for a representative member of each subgroup are given in Table 3-XV.

Before beginning the systematic descriptions, it is well to note that all lunar samples, especially the breccias, are more-or-less fractured. Each sample has through-going fractures that are commonly branched. In some cases (e.g., the Apollo 14 breccias), these fractures are so abundant that the samples are dominated by the fractures and the debris of the fracture zones.

a. Vitric-Matrix Breccias:

Vitric-matrix breccias consist of an assemblage of mineral, glass, and rock fragments bound together by grain-to-grain sintering and by smaller glass fragments that act as cement. Samples range from very friable to tough. These rocks are very porous; they commonly have bulk densities between 2.0 and 3.0. Polished surfaces display a network of micrometer-size fractures and irregular cavities whose abundance is an inverse function of the sample's density. The shapes of fragments vary from angular to subrounded. Size distribution of the fragments is such that as the size decreases, the abundance increases. Detailed study of size distribution for lunar materials has not been accomplished. Similar suites of terrestrial materials, however, follow a log-log

TABLE 3-XV.—Chemistry of Breccias

Chemical	Mare		Highland							
	Vitric matrix						Crystalline matrix			
	Low Ti	High Ti	KREEP	Anor. gabbro	Light matrix	Cata. Anor.	KREEP		Anor. gabbro	Gran. matrix
	For sample number —									
	12034	10060	14047	60255	14063	60025	14305	76015	68415	79215
	Weight percent									
SiO_2	47.8	40.0	47.2	45.2	45.5	45.3	48.3	46.2	45.3	43.8
TiO_2	2.3	8.5	1.7	.69	1.3	.02	1.5	1.5	.3	.3
Al_2O_3	15.5	11.3	18.2	26.1	23.0	34.2	16.2	17.2	28.7	27.7
Cr_2O_3	—	.3	.1	.1	.16	.003	.2	.2	.1	.2
FeO	12.4	17.7	10.5	5.9	5.8	.5	10.4	9.8	4.1	4.6
MnO	.2	.2	.1	.06	.1	.008	.1	.1	.05	.06
MgO	8.3	7.7	8.9	6.4	9.6	.2	10.3	13.0	4.3	6.3
CaO	10.8	14.5	11.5	15.1	13.0	19.8	9.9	10.8	16.2	15.9
Na_2O	.7	.5	.7	.5	.7	.5	.8	.7	.5	.5
K_2O	.5	.2	.5	.1	.1	.1	.6	.3	.09	.1
P_2O_5	.5	.1	.5	.1	—	—	.6	.3	.06	.4
S	.09	.15	.08	.04	—	—	—	.09	—	—
Total	99.1	101.15	99.98	100.29	99.26	100.63	98.90	100.19	99.70	99.86
	Trace chemicals									
Li ppm	18	7	—	—	—	—	38.4	21.6	5.1	—
Rb ppm	—	4	16	—	3.5	.1	25	6.57	1.9	—
Sr ppm	—	180	180	—	235	213.6	190	177	140	—
Ba ppm	720	250	730	140	460	10	830	358	70	—
La ppm	—	24	80	12.6	19.4	.28	109	33.4	6.81	2.65
Ce ppm	176.7	62	235	35	47	.65	200	84.9	16.3	6.8
Nd ppm	92	82	102	—	36	.42	140	54	9.92	—
Sm ppm	28.3	24	28	—	9.17	.092	23	15.2	2.88	1.19
Eu ppm	2.69	2	2.6	1.3	2.55	1.04	2.6	1.99	1.13	.84
Gd ppm	—	28	31	—	11.6	.0895	38	18.9	3.27	—
Dy ppm	—	41	33	—	12	.19	43	19.9	3.62	—
Er ppm	—	30	19	—	7	.05	32	11.7	2.18	—
Yb ppm	21.7	22	17	—	6.8	.048	—	10.8	2	1.37
Lu ppm	3.14	2	3	0.7	.99	.0056	3.5	1.3	.33	.24
Zr ppm	630	580	780	—	325	.48	—	507	72	—
Hf ppm	20.4	13	17	5.2	11	.02	26	12.9	—	—
Th ppm	13	3	12	5.2	3.2	—	17.4	5.56	—	—
U ppm	3	.6	3.2	—	.82	.135	5.15	1.96	445	—
Ir ppb	—	—	11.2	12.2	1.37	0057	10	3.41	4.58	21.3
Re ppb	—	—	1.06	—	064	0016	—	.315	.434	1.90
Au ppb	—	—	5.4	5.6	28	0074	6.7	1.89	2.65	8.27
Ni ppm	—	70	—	391	—	1.1	200	135	184	255
Sb ppb	—	5	2.1	—	1.3	035	—	1.02	.53	2.79
Ge ppb	—	1400	—	912	36	2.3	440	164	73	33
Se ppb	—	90	320	—	8	21.7	—	76	98	176
Te ppb	—	—	85	—	3	6.75	—	—	13.5	17
Ag ppb	—	10	11	—	87	3.4	—	1.02	4 8	1.16
Bi ppb	—	—	1 1	—	28	.36	—	22	.45	16
Zn ppb	—	25	20	21	5.3	3.25	2.1	2.8	4 8	2.3
Cd ppb	—	300	102	60.8	18	5	—	3.2	2.75	98
Tl ppb	—	—	17	—	5.6	1 76	—	67	.49	.41

law with a -2 to -3 slope (i.e., a decrease in size by a factor of 10 would be accompanied by an increase in abundance by a factor of between 100 and 1000).

Composition of the included mineral and rock fragments is similar to the composition of analogous material in the surrounding regolith.

Vitric-matrix breccias may be considered as compacted and lithified regolith, and there are no major chemical differences between local regolith and local vitric-matrix breccias. Vitric-matrix breccias have been referred to as soil breccias, regolith breccias, and glassy breccias. Vitric-matrix breccias even contain enriched abundances of solar-wind-derived components such as the noble gases, carbon, nitrogen, and hydrogen.

Vitric-matrix breccias are abundant on the lunar surface. All breccias returned from the maria and approximately one-third of the breccias returned from the highlands are vitric-matrix breccias.

b. Light-Matrix Breccias:

Light-matrix breccias are similar in texture and friability to the vitric-matrix breccias except they lack glass fragments. They are but poorly bonded aggregates of mineral and rock fragments that are cemented together by grain-to-grain sintering. The light-matrix breccias may be thought of as "glass-free" vitric-matrix breccias.

Light-matrix breccias occur in the lunar samples returned from the Apollo 14 and 16 sites only. From various indirect data, one may hypothesize that light-matrix breccias make up approximately 10 or 15 percent of the lunar highlands.

c. Cataclastic Anorthosites:

Cataclastic anorthosites are crushed rocks consisting of 50 to 99 percent plagioclase feldspar. These samples are very friable. They consist of angular fragments of plagioclase, pyroxene, and olivine, bound together by tiny amounts of glass or by grain-to-grain sintering. Fragment sizes vary from approximately a micrometer to several centimeters, and pore space ranges from 20 percent to essentially nil.

Mineral compositions for cataclastic anorthosite are given in Table 3-XVI. For the most part, minerals in these rocks are "pure," in that plagioclase feldspar contains low amounts of iron and pyroxenes and olivines are Mg-rich and Fe-poor. Many of the plagioclase feldspars contain submicron rods and blebs of an opaque phase, probably Fe-metal of FeS.

Approximately two-thirds of the cataclastic anorthosites returned during the Apollo Program contain more than 80 percent plagioclase. However, the proportion of samples with this abundance of plagioclase varies from site to site.

TABLE 3-XVI.— Chemical Composition of Minerals From Cataclastic Anorthosites (wt.%)

Chemical	*Plagioclase*	*Olivine*	*Low-Ca pyroxene*	*Low-Ca pyroxene*	*High-Ca pyroxene*	*Cr-spinel*	*Ilmenite*	*Troilite*
SiO_2	43.56	35.59	53.20	51.25	50.88	0.03	0.01	0.01
TiO_2	.01	.01	.35	.28	.61	2.82	53.24	<.01
Al_2O_3	35.94	<.01	.72	.72	1.50	13.14	<.01	—
Cr_2O_3	—	.05	.33	.27	.37	48.66	.33	<.01
MgO	.03	30.11	24.37	19.89	13.04	3.08	3.27	<.01
FeO	.17	34.58	19.72	24.49	11.98	31.77	42.24	63.84
MnO	—	.42	.35	.41	.37	.74	.50	<.01
CaO	20.00	.03	1.10	1.69	21.22	—	—	.03
BaO	<.01	—	—	—	—	—	—	—
Na_2O	.26	—	.01	<.01	.01	—	—	—
K_2O	.01	—	—	—	—	—	—	—
ZrO_2	—	—	—	—	—	.08	<.01	—
V_2O_3	—	—	—	—	—	.55	<.01	—
Nb_2O_5	—	—	—	—	—	<.01	<.01	—
NiO	—	.03	—	—	—	—	—	<.01
Co	—	—	—	—	—	—	—	<.01
S	—	—	—	—	—	—	—	37.76
Total	99.98	100.82	100.15	99.00	99.98	100.87	99.59	101.64

NOTE: Modal mineralogy, vol.% — plagioclase, 83 percent; olivine, 16 percent; pyroxene, 1 percent; and opaques, less than 1 percent.

Cataclastic anorthosites are rare at all landing sites. Approximately 5 percent of the material returned from the highlands is in this category of material.

d. Crystalline-Matrix Breccias:

Crystalline-matrix breccias consist of a fine-grain, uniform matrix with embedded mineral and rock clasts. The matrix consists of interlocking crystals of plagioclase feldspar, pyroxene, olivine, and ilmenite with sizes ranging from 1 to 100 micrometers. The interlocking of crystals in the matrix bonds the total rock together. Most samples are tough with a low porosity (0.5 to 4 percent). Pore spaces vary from 0.1 millimeter to 10 centimeters; they may be spherical or irregular cavities. Additional cavities, which are 5 to 50 micrometers in size and polygonal in shape, occur interstitial to the crystals in some regions of the matrix. Clasts range in size from 50 micrometers to tens of meters; they consist of abundant plagioclase with less abundant olivine and even less abundant pyroxene plus rocks.

Crystalline-matrix breccias are chemically equilibrated in that all crystals and grains of a given mineral in each sample have approximately the same composition. Thus, both matrix plagioclase and plagioclase clasts share the same composition in each sample, and that composition is different for different samples. Typical mineral compositions are given in table 3-XVII.

Crystalline-matrix breccias occur only in the highlands, where they comprise approximately 50 percent of the samples returned.

TABLE 3-XVII.— Chemical Composition and Modal Mineralogy for Minerals From Crystalline-Matrix Breccias (wt.%)

(a) Sample 14310: coarser-grain matrix with few clasts

Chemical	*Plagioclase*	*Low-Ca pyroxene*	*High-Ca pyroxene*	*Olivine*	*Ilmenite*	*Troilite*	*Metal*	*Calcium phosphide*	*Mesostasis*	*Bulk composition*
P_2O_5	—	—	—	—	—	—	—	43.15	0.08	0.44
SiO_2	46.67	53.53	50.81	37.66	0.21	—	—	—	57.98	46.47
TiO_2	.02	.90	1.87	.09	54.16	.01	<.01	—	1.82	1.50
Al_2O_3	33.51	.99	1.95	.02	<.01	—	—	—	23.14	17.52
Cr_2O_3	—	.50	.64	.15	.44	—	—	—	.03	.20
CaO	17.78	2.43	18.74	.16	—	.08	.01	54.54	5.29	11.50
MgO	.09	26.36	17.08	35.76	6.56	03	<.01	—	.76	12.46
FeO	.25	15.42	8.65	26.24	37.38	63.17	92.58	—	1.40	8.96
MnO	—	.19	.21	.32	.46	—	—	—	<.01	.11
BaO	<.01	—	—	—	—	—	—	—	.90	.01
Na_2O	1.51	.06	.17	—	—	—	—	—	.53	.79
K_2O	.13	—	—	—	—	—	—	—	7.21	.13
ZrO_2	—	—	—	—	.01	—	—	—	.07	<.01
V_2O_3	—	—	—	—	<.01	—	—	—	—	<.01
Nb_2O_5	—	—	—	—	.13	—	—	—	—	<.01
NiO	—	—	—	<.01	—	.04	6.99	—	—	.02
Co	—	—	—	—	—	<.01	.37	—	—	<.01
S	—	—	—	—	—	38.52	<.01	—	<.01	.09
F	—	—	—	—	—	—	—	2.31	—	.02
Total	99.96	100.38	100.12	100.40	99.35	101.85	99.96	100.00	99.22	100.22
Vol.%	56.2	25.4	5.9	8.8	1.3	0.1	0.0	0.9	1.0	Calculated
$\pm 1\sigma$	2.0	1.4	.6	.8	.3	.1	0	.2	.2	(1307
Wt.%	50.4	28.4	6.5	10.2	2.0	.2	.2	1.0	.8	points)

TABLE 3-XVII.— Concluded

(b) Sample 72395: finer-grain matrix with abundant clasts

Chemical	Orthopyroxene		Pigeonite and ferropigeonite		Augite		Plagioclase		K-feldspar	Glass	
SiO_2	52.2	51.8	50.8	47.1	49.6	48.4	44.0	50.9	62.0	76.8	30.5
Al_2O_3	3.44	1.58	1.35	.95	2.81	1.91	34.8	30.0	18.9	11.1	3.08
TiO_2	.69	.65	.89	.74	1.53	1.85	—	—	—	.89	14.6
Cr_2O_3	.61	.48	.39	.08	.72	.04	—	—	—	—	—
FeO	11.2	16.1	19.8	34.1	13.5	18.3	.08	.39	.25	.86	35.7
MnO	.21	.28	.33	.47	.26	.29	—	—	—	.04	.36
MgO	28.4	24.8	20.3	9.17	16.4	11.4	—	—	—	.02	3.16
CaO	2.50	3.11	5.07	5.74	14.0	16.4	19.1	14.5	.37	.73	7.09
Na_2O	.02	.03	.02	.04	.09	.11	.64	2.86	.90	.94	.40
K_2O	—	—	—	—	—	—	.05	.73	14.2	7.39	.52
Total	99.3	98.8	99.0	98.4	98.9	98.7	98.6	99.4	96.7	98.8	95.4

e. Granulitic-Matrix Breccias:

Granulitic breccias are metamorphosed rocks that consist of a crystalline matrix and sparse mineral and rock clasts. These materials are tough, having virtually no porosity. The rocks are bound by the interlocking minerals of the matrix. The matrix consists of plagioclase feldspar and olivine and/or pyroxene in crystals on the order of 50 micrometers in some samples and 200 micrometers in others.

Mineral compositions are the same for the matrix minerals as for the minerals that appear as clasts. Table 3-XVIII gives the mineral chemistry for some typical granulitic breccias.

Granulitic breccias are rare on the lunar surface. Only five large rocks returned during the Apollo Program are granulitic breccias (four during Apollo 17 and one during Apollo 16). However, rock clasts in other breccias and fragments in the regolith that are granulitic breccias have been found at all the landing sites. This suggests that granulitic breccias may be common at depths of a few kilometers throughout the highlands.

TABLE 3-XVIII.— *Chemical Composition of Minerals From Granulitic-Matrix Breccias (wt.%)*

(a) Sample 77017; coarser-grain matrix

Chemical	Pyroxene				Olivine	Plagioclase	Spinel	Chromite	Ilmenite	Glass
SiO_2	52.32	53.78	52.31	53.62	36.49	44.81	—	—	—	43.76
TiO_2	1.11	.69	.80	.71	.05	.04	0.23	14.72	53.82	.44
Al_2O_3	2.06	.70	1.95	.84	.00	35.50	62.93	8.27	.04	25.21
Cr_2O_3	.81	.36	.77	.43	.04	—	4.02	33.00	.31	—
FeO	9.25	20.17	10.54	18.25	33.73	.12	16.27	39.63	41.25	6.40
MnO	.20	.35	.20	.31	.32	—	.10	.35	.42	—
MgO	14.96	22.96	15.74	21.60	29.06	.05	16.57	4.25	4.38	6.37
CaO	19.19	1.64	17.44	4.09	.18	19.46	—	—	—	14.87
Na_2O	—	—	—	—	—	.42	—	—	—	.35
K_2O	—	—	—	—	—	.14	—	—	—	.05
Total	99.90	100.65	99.75	99.85	99.87	100.54	100.12	100.22	100.22	97.45

(b) Sample 79215; finer-grain matrix

Chemical	Plagioclase	Olivine	Low-Ca pyroxene	High-Ca pyroxene	Whole rock
SiO_2	44.4	37.8	54.9	51.3	43.8
TiO_2	—	.06	.6	1.7	.3
Al_2O_3	35.4	.03	1.0	2.4	27.7
Cr_2O_3	—	.03	.3	.6	.2
FeO	.5	25.0	14.9	7.2	4.6
MnO	—	.3	.2	.2	.06
MgO	—	37.4	27.5	16.4	6.3
CaO	18.5	.1	1.7	20.4	15.9
Na_2O	.6	.0	.0	.1	.5
K_2O	.2	—	—	—	.1
Total	99.6	100.7	101.1	100.3	99.5

C. Propellant Production From Lunar Materials

1. Terrestrial Production

Propellant grade O_2 is produced by well understood air liquefaction techniques. While this simple method will not be available on the moon, many of the techniques and processes for liquefaction, transport and storage of O_2 will be of use in the design, fabrication and operation of a lunar facility.

Silanes can be prepared by the action of mineral acids upon crude magnesium silicide, Mg_2Si, that results from the reduction of silica by magnesium (Reference 1). Strock reported hydrides corresponding to one fourth of the silicon contained in the Mg_2Si were obtained in the proportions 40% SiH_4, 30% Si_2H_6 15% Si_3H_8, 10% Si_4H_{10}, and the remainder as higher hydrides (References 4, 5 and 6).

Note the Mg_2Si produced from the reduction of SiO_2 with Mg is not pure Mg_2Si. In addition to magnesium and silicon, it contains oxygen, perhaps, apart from true silicide, there are present magnesium oxide, magnesium silicate, and "hyposilicates" that may play a part in the production of the silicon hydride (Reference 6).

Much better yields of SiH_4 are obtained by Finholt's method, the reaction of lithium aluminum hydride with silicon tetrachloride (References 7 and 8). Unfortunately, this synthesis may be

$$SiCl_4 + LiAlH_4 = SiH_4 + LiCl + AlCl_3$$

too complex for lunar application.

Silane has become an article of commerce in the electronics industry as noted in Appendix A. Additional synthesis and production information of values may be found.

2. Lunar Production

The production of O_2 on the moon by the reduction of lunar ilimenite with hydrogen has been considered

(Reference 8). Based upon the

$$2\ FeTiO_3 + 2\ H_2 = 2\ Fe + 2\ H_2O + 2\ TiO_2$$

$$2\ H_2O + e = 2\ H_2 + O_2$$

occurrence of ilimenite (Table 2-VIII) high titanium mare basalts may be considered as potential ores for this mineral.

The production of O_2 on the moon by the carbothermal reduction of lunar pyroxene and olivine with methane has been considered (Reference 10). Mare basalts may be considered as

$$MgSiO_3 + 2\ CH_4 = 2\ CO + 4\ H_2 + Si + MgO$$

$$2\ CO + 6\ H_2 = 2\ CH_4 + 2\ H_2O$$

$$2\ H_2O + e = 2\ H_2 + O_2$$

$$Mg_2SiO_4 + 2\ CH_4 = 2\ CO + 4\ H_2 + Si + 2\ MgO$$

$$2\ CO + 6\ H_2 = 2\ CH_4 + 2\ H_2O$$

$$2\ H_2O + e = 2\ H_2 + O_2$$

potential ores for these minerals (Tables 2-II and 2-IV)

The carbothermal process, although more complex than the simple reduction process, has several advantages i.e., the minerals pyroxene and olivine are in much greater abundance on the Moon than ilmenite (Table 2-I), more of the O_2 contained in the ore is converted to propellant, and the byproduct magnesium oxide may be used to produce silane in combination with

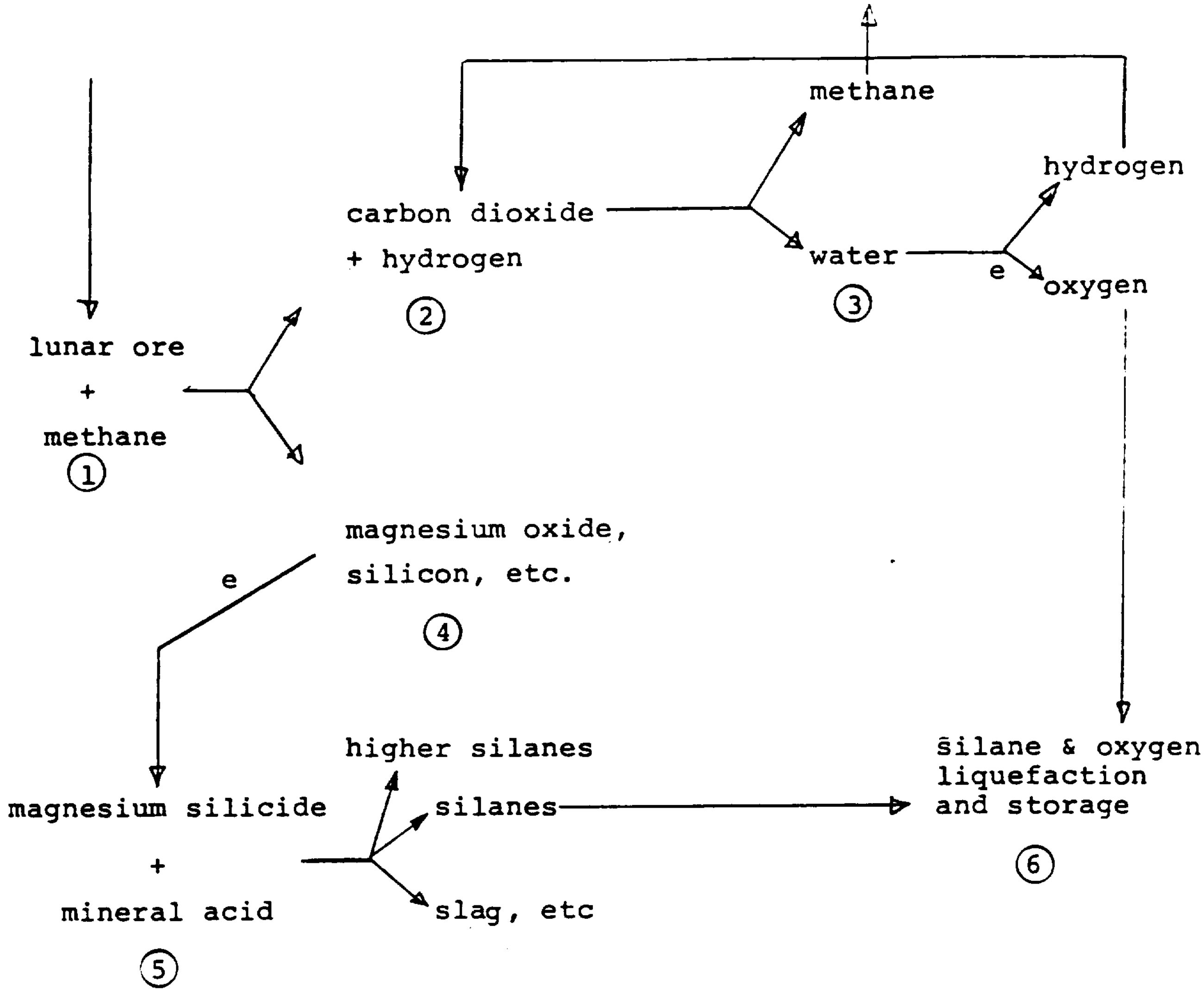
$$2\ MgO + e = 2\ Mg + O_2$$

$$2\ Mg + Si = Mg_2Si$$

$$Mg_2Si + 4\ HCl = SiH_4 + 2\ MgCl_2$$

higher silanes (References 1, 4, 5 and 6). Of course, research and development would be required to maximize the yield and purity of the SiH_4. This is true of all lunar processes. Mineral acid would have to be resupplied from earth.

An integrated propellant production facility can be considered which is based on the use of mare basalts which are rich in pyroxene (enstatite, $MgSiO_3$) and/or olivine (forsterite, Mg_2SiO_4) as indicated in Figure 4. More detailed analysis of such a facility is worthy of additional study.



1. carbothermal reduction furnace
2. pipeline gas catalytic tower
3. water electrolysis cell
4. magnesium oxide electrolysis cell
5. silane reactor and separator
6. propellant liquefaction (including purification and analysis certification) and storage/transfer facility

Figure 4

The Integrated Lunar Production of Oxygen and Silane is Feasible

APPENDIX A

ADDITIONAL REFERENCES FOR SILANE:

PROPERTIES AND PRODUCTION

894484 PB82-157603
Systematic Sila Substitution of Pharmaca (Systematische Sila-Substitution Von Pharmaka)
Bentlage, Anke
Technische Univ., Brunswick (Germany, F.R.). Naturwissenschaftliche Fakultaet (1).
Corp. Source Codes: 034107009
Mar 81 126p
Text in German.
Languages: German Document Type: Thesis
NTIS Prices: PC A07/MF A01 Journal Announcement: GRAI8210
Country of Publication: Germany, Federal Republic of
Sila analoga of representatives of three biologically active substance classes are synthesized and investigated, with special emphasis on the problem of the effects of the physico-chemical properties of the substances changed by sila substitution on their pharmacological behavior. A description is given of three methods used, followed by the observation and investigation of a new thermally induced reaction proceeding under intramolecular 1.2 hybrid shifting and decarboxylation. The finding is that thermal treatment of (hydroxymethyl) methyl phenyl silane led surprisingly to the unusually stable hexagonal ring 49, whose constitution could be uniquely assured. This composition seems to represent the first stable representative of this type. The article is followed by a literature review of 127 references.
Descriptors: *Silicon organic compounds; *Drugs; *Synthesis(Chemistry); *Molecular structure; Substitution reactions; Silanes; Theses; Hybridization
Identifiers: *Foreign technology; Silane/(hydroxymethyl)-methyl-phenyl; Thermal treatment; NTISTFESA
Section Headings: 6O (Biological and Medical Sciences--Pharmacology); 57O (Medicine and Biology--Pharmacology and Pharmacological Chemistry)

841536 DOE/JPL/954343-21
Process Feasibility Study in Support of Silicon Material Task I. Final Report, October 1, 1975-February 6, 1981
Yaws, C. L. ; Li, K. Y. ; Hopper, J. R. ; Fang, C. S. ; Hansen, K. C.
Lamar Univ., Beaumont, TX. Dept. of Chemical Engineering.
Corp. Source Codes: 064173001; 9502479
Sponsor: Department of Energy, Washington, DC.
6 Feb 81 452p
Languages: English
NTIS Prices: PC A20/MF A01 Journal Announcement: GRAI8116 ; NSA0600
Country of Publication: United States
Contract No.: NAS-7-100-954343
The Low-Cost Solar Array (LSA) Project is directed toward effective cost reduction in the production of silicon for solar cells. Results are presented for process system properties, chemical engineering and economic analyses of the new technologies and processes being developed for the production of lower cost silicon for solar cells. Major physical, thermodynamic and transport property data are reported for the following silicon source and processing chemical materials: silane, silicon tetrachloride, trichlorosilane, dichlorosilane, silicon tetrafluoride, and silicon. The property data are reported for critical temperature, critical pressure, critical volume, vapor pressure, heat of vaporization, heat capacity, density, surface tension, viscosity, thermal conductivity, heat of formation and Gibb's free energy of formation. Chemical engineering analyses involving the preliminary process design of a plant (1000 MT/yr capacity) to produce silicon via the technology under consideration were accomplished for the following processes: UCC silane process for silicon, BCL process for silicon, conventional polysilicon process (Siemens technology), SiI sub 4 decomposition process, and DCS process (dichlorosilane).Major activities in chemical engineering analyses include base case conditions, reaction chemistry, process flowsheet, material balance, energy balance, property data, equipment design, major equipment list, production labor and forward for economic analysis. The process design package provides detailed data for raw materials, utilities, major process equipment and production labor requirements necessary for polysilicon production in each process. Using detailed data from the process design package, economic analyses for a 1000 MT/yr silicon plant were accomplished. Primary results from the economic analyses included plant capital investment and product cost. Results are presented and discussed. (ERA citation 06:012159)
Descriptors: Chemical reactions; Chlorine compounds; Critical pressure; Critical temperature; Data compilation; Density; Diagrams; Economic analysis; Engineering; Equipment; Formation free enthalpy; Formation heat; Graphs; Industrial plants; Physical properties; Production; Raw materials; Silanes; *Silicon; Silicon chlorides; Silicon fluorides; Silicon solar cells; Specific heat; Surface tension; Temperature dependence; Thermal conductivity; Thermodynamic properties; Vapor pressure; Vaporization heat; Viscosity
Identifiers: ERDA/140501; ERDA/360601; ERDA/360603; NTISDE
Section Headings: 10B (Energy Conversion (Non-propulsive)---Power Sources); 7A (Chemistry--Chemical Engineering); 97N (Energy--Solar Energy); 99B (Chemistry--Industrial Chemistry and Chemical Process Engineering)

767877 DOE/JPL/954334-10
Low Cost Solar Array Project. Feasibility of the Silane Process for Producing Semiconductor-Grade Silicon. Final Report, October 1975-March 1979
Union Carbide Corp., New York.
Corp. Source Codes: 6431500
Sponsor: Department of Energy, Washington, DC.
Jun 79 365p
Languages: English
NTIS Prices: PC A16/MF A01 Journal Announcement: GRAI8015 ; NSA0500
Country of Publication: United States
Contract No.: NAS-7-100-954334
The commercial production of low-cost semiconductor-grade silicon is an essential requirement of the JPL/DOE (Department of Energy) Low-Cost Solar Array (LSA) Project. A 1000-metric-ton-per-year commercial facility using the Union Carbide Silane Process will produce molten silicon for an estimated price of $7.56/kg (1975 dollars, private financing), meeting the DOE goal of less than $10/kg. Conclusions and technology status are reported for both contract phases, which had the following objectives: (1) establish the feasibility of Union Carbide's Silane Process for commercial application, and (2) develop an integrated process design for an Experimental Process System Development Unit (EPSDU) and a commercial plant facility, and estimate the corresponding commercial plant economic performance. To assemble the facility design, the following work was performed: (a) collection of Union Carbide's applicable background technology; (b) design, assembly, and operation of a small integrated silane-producing Process Development Unit (PDU); (c) analysis, testing, and comparison of two high-temperature methods for converting pure silane to silicon metal; and (d) determination of chemical reaction equilibria and kinetics, and vapor-liquid equilibria for chlorosilanes. (ERA citation 05:013256)
Descriptors: *Silanes; *Silicon; Casting; Chemical reaction kinetics; Chemical reactions; Chemical reactors; Chlorine compounds; Computer calculations; Cost; Data; Design; Distillation; Economics; Equilibrium; Equipment; Feasibility studies; Fluidized bed; Formation heat; Hydrogenation; Impurities; Industrial plants; Mathematical models; Operation; Performance; Physical properties; Powders; Process control; Processing; Production; Purification; Pyrolysis; Reaction heat ; Research programs; Silicon chlorides; Silicon solar cells; Sintering; Specifications; Tables; Thermodynamics; Waste disposal
Identifiers: ERDA/140501; ERDA/360601; NTISDE
Section Headings: 7A (Chemistry--Chemical Engineering); 10B (Energy Conversion (Non-propulsive)--Power Sources); 97N (Energy--Solar Energy); 99B (Chemistry--Industrial Chemistry and Chemical Process Engineering)

754998 AD-B009 740/2
Improved CVD Techniques for Depositing Passivation Layers of ICs
(Final rept. 22 Apr 74-30 Jun 75)
Kern, Werner ; Comizzoli, Robert B. ; Fisher, A. Wayne ; Schnable, George L.
RCA Labs., Princeton, NJ.
Corp. Source Codes: 007729000; 299000
Report No.: PRRL-75-CR-38; AFML-TR-75-160
Oct 75 256p
DDC Form 55 not necessary for document request.
Distribution limitation now removed.
Languages: English
NTIS Prices: PC A12/MF A01 Journal Announcement: GRAI8010
Country of Publication: United States
Contract No.: F33615-74-C-5146; AF-7371; 737174
This report describes the results of studies to increase the understanding of the requirements for successful glass passivation, by chemical vapor deposition (CVD), of metallized silicon planar integrated circuits (ICs) to improve both performance and reliability. The effects of various conditions for low-temperature (350 to 450 C) CVD of phosphosilicate glass (PSG) layers by oxidation of silane plus phosphine were correlated with the physical and chemical properties of deposited films. It is concluded that the important conditions to control are substrate temperature of deposition, oxygen-to-hydride ratio, hydride input, silane-to-phosphine ratio, and nitrogen input.
Descriptors: *Integrated circuits; Manufacturing; Vapor deposition; Passivity; Semiconductor devices; Layers; Glass; Films; Silicon coatings; Phosphine; Silanes; Silica glass; Phosphate glass; Aluminum; Corrosion; Failure; Nitrogen; Degradation; Phosphorus; Silicon dioxide; Electrical properties; Chemical properties; Impurities; Dielectrics
Identifiers: *Chemical vapor deposition; Hydrides; NTISDODXD
Section Headings: 20L (Physics--Solid-state Physics); 46D (Physics--Solid State Physics)

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TABLE 1

PROPERTIES OF SILANE, SiH_4

		O_2
Melting Point, °C	-185	-218
Boiling Point, °C	-112	-183

H_{fusion}, cal/mol	159.5
$H_{vapor.}$, cal/mol	2982
$H_{formation}$, cal/mol	7800
Entropy ΔS, std.	48.7

Density liquid at -185°C, 0.68 g/ml
Surface tension at -112°C, 15.11 dynes

Vapor Pressure

$$\log_{10} p = -\frac{662.8}{T} + 6.996 \quad \text{where } p = \text{mmHg}, \; T = °K$$

Calculated p:

T		p	
°F	°C	mmHg	psia
-256	-160	13.7	0.26
-220	-140	104.	2.0
-200	-129	255.	4.9
-181	-118	530.	10.3
-170	-112	760.	14.7

Critical Temperature, °C -3.5

Critical Pressure, psia 703.

TABLE 2

INTEGRATED SCHEME USING ILMENITE AND IRON SILICIDE TO PRODUCE SILANE

$$2\ FeTiO_3 + 2\ H_2 \longrightarrow 2\ Fe + 2\ TiO_2 + 2\ H_2O$$
$$2\ Fe + Si \longrightarrow Fe_2Si$$
$$Fe_2Si + 4\ H_2O \longrightarrow SiH_4 + 2\ Fe(OH)_2$$
$$2\ Fe(OH)_2 \longrightarrow 2\ FeO + H_2O$$
$$2\ H_2O + 2\ e \longrightarrow 2\ H_2 + O_2$$

$$2\ FeTiO_3 + SiO_2 + 3\ H_2O + 3e \longrightarrow SiH_4 + 2\ TiO_2 + 2\ FeO + 2\ O_2$$

$$SiO_2 + 4\ HF \longrightarrow SiF_4 + 2\ H_2O$$
$$2\ H_2O + 2\ e \longrightarrow 2\ H_2 + O_2$$
$$SiF_4 + 2\ H_2 \longrightarrow Si + 4\ HF$$

$$SiO_2 + e \longrightarrow Si + O_2$$

661139 DOE/JPL/954343-77/4
Process Feasibility Study In Support of Silicon Material, Task I. Quarterly Technical Progress Report (IX)
Fang, C. S. ; Hansen, K. C. ; Miller, Jr., J. W. ; Yaws, C. L.
Lamar Univ., Beaumont, Tex. Dept. of Chemical Engineering.
Corp. Source Codes: 9502479
Sponsor: Department of Energy.
Dec 77 27p
NTIS Prices: PC A03/MF A01 Journal Announcement: GRAI7820 ; NSA0300
Contract No.: NAS-7-100-954343
Major activities were devoted to process system properties, chemical engineering and economic analyses. Analyses of process system properties were continued for silicon source materials under consideration for solar cell grade silicon production. Major activities focused on properties of silicon tetrachloride which is the source material for several alternate processes. Status and progress are reported for vapor pressure, heat of vaporization, heat capacity, density, surface tension, viscosity, thermal conductivity, heat of formation and Gibb's free energy of formation. Experimental thermal conductivity values for hydrogen, determined for instrument accuracy evaluation, were in very good agreement with recommended values from the literature. The deviations were only +-2% up to 300 exp 0 C. Preliminary results for gas phase thermal conductivity are reported for silane (SIH sub 4) and dichlorosilane (SIH sub 2 Cl sub 2) in the respective temperature ranges, 25 to 300 exp 0 C and 25 to 400 exp 0 C. There have been no previously reported experimental data in the literature for these silicon source materials. Major efforts were continued on the preliminary process design of the silane process. Progress and status are reported for key items. The process flow diagram, material balance and energy balance are 100% complete for the revised flowsheet. Major process equipment design is 85% complete. Estimate of production labor requirements is 75% complete. (ERA citation 03:037061)
Descriptors: *Hydrogen; *Silanes; Silicon; *Silicon chlorides; Density; Fabrication; Formation free enthalpy; Formation heat; Physical properties; Production; *Silicon solar cells; Specific heat; Surface tension; Thermal conductivity; Vapor pressure; Vaporization heat; Viscosity
Identifiers: ERDA/140501; ERDA/360601; ERDA/360601; Photovoltaic cells; Reduction(Chemistry); NTISDE
Section Headings: 10B (Energy Conversion (Non-propulsive)---Power Sources); 97N (Energy--Solar Energy)

656628 N78-23561/1
Process Feasibility Study in Support of Silicon Material Task 1
(Quarterly Technical Progress Report)
Fang, C. S. ; Hansen, K. C. ; Miller, Jr., J. W. ; Yaws, C. L.
Lamar Univ., Beaumont, Tex. Chemical Engineering Dept.
Report No.: NASA-CR-157030; ERDA/JPL-954343-78/1
Mar 78 81p
NTIS Prices: PC A05/MF A01 Journal Announcement: GRAI7818 ; STAR1614
Contract No.: JPL-954343
Initial results for gas thermal conductivity of silicon tetrafluoride and trichlorosilane are reported in respective temperature ranges of 25 to 400 C and 50 to 400 C. For chemical engineering analyses, the preliminary process design for the original silane process of Union Carbide was completed for Cases A and B. Regular and Minimum Process Storage. Included are raw material usage, utility requirements, major process equipment lists, and production labor requirements. Because of the large differences in surge tankage between major unit operations the fixed capital investment varied from $19,094,000 to $11,138,000 for Cases A and B, respectively. For the silane process the original flowsheet was revised for a more optimum arrangement of major equipment, raw materials and operating conditions. The initial issue of the revised flowsheet (Case C) for the silane process indicated favorable cost benefits over the original scheme.
Descriptors: *Economic analysis; *Production engineering; *Silanes; *Silicon tetrachloride; Costs; Gaseous diffusion; Physical properties; *Silicon solar cells; Thermodynamic properties; Transport properties
Identifiers: Photovoltaic cells; NTISNASA
Section Headings: 10B (Energy Conversion (Non-propulsive)---Power Sources); 97N (Energy--Solar Energy)

639462 AD-284 510/5
The Reaction of Methylchlorosilane and SiCl4 with N,N'-Bis-(Trimethsilyl-) Ethylenediamine
KUMMER, D. ; ROCHOW, E.G.
Harvard Univ Cambridge Mass Mallinckrodt Lab
Corp. Source Codes: 215100
Jun 62 32p
Distribution limitation now removed. NOTE: Only 35mm microfilm is available. No microfiche.
NTIS Prices: PC A03/MF A01 Journal Announcement: GRAI7813
Contract No.: Nonr-1866(13)
No abstract available.
Descriptors: Chlorides; *Ethyleneamines; *Methyl radicals; *Silanes; Silicon compounds; Chemical reactions; Heterocyclic compounds; Lithium compounds; Molecular structure; Physical properties
Identifiers: *Synthesis(Chemistry); Silane/methyl-chloro; Silane/tetrachloro; Ethylene diamine/N-N-bis(trimethyl-silyl); NTISDODXD
Section Headings: 7C (Chemistry--Organic Chemistry)

544374 ERDA/JPL/954343-76/2
Process Feasibility Study in Support of Silicon Material Task I. Quarterly Technical Progress Report (II)
Yaws, C. L.
Lamar Univ., Beaumont, Tex. Dept. of Chemical Engineering.
Corp. Source Codes: 9502479
Sponsor: Energy Research and Development Administration.
Apr 76 29p
For Jet Propulsion Lab., Pasadena, CA.
NTIS Prices: PC A03/MF A01 Journal Announcement: GRAI7704 ; NSA0200
Contract No.: 954343

Preliminary data collection is very near completion for the silicon source materials--silane (SIH sub 4), silicon tetrachloride (SICl sub 4), and silicon tetraiodide (SII sub 4)----which are associated with the silane, Zn/SICl sub 4 , and H sub 2 /SII sub 4 processes under consideration. Major effort was initiated on the silicon source materials--silicon tetrafluoride (SIF sub 4) and silicon difluoride (SIF sub 2)--for the transport process. Preliminary results for the critical constants and physical properties of silane (SIH sub 4) were tabulated. Initial background technical information exchange was accomplished on the following processes in the task integration meeting and subsequent discussions: Zn/SICl sub 4 (Battelle); H sub 2 /SII sub 4 (Batelle); silane (Union Carbide); transport (Motorola); induction plasma (Texas Instruments); arc furnace (Dow Corning), and SIF sub 4 reduction (Stanford). Several base case conditions including a plant size of 1000 metric tons/yr. were tentatively suggested and selected. Three such plants would provide the required 3000 metric tons/yr. of solar cell grade silicon. Procurement of data sources for numerous equipment types was accomplished for use in economic analysis. A review of methods for estimating capital investment was also initiated. (ERA citation 02:000440)

Descriptors: •Silicon; Chemical preparation; Cost; Feasibility studies; Silanes; Silicon fluorides; Silicon iodides

Identifiers: ERDA/140501; •Silicon solar cells; Photovoltaic cells; Fabrication; Reduction(Chemistry); NTISERDA

Section Headings: 10B (Energy Conversion (Non-propulsive)---Power Sources); 7D (Chemistry--Physical Chemistry); 97N (Energy--Solar Energy); 99F (Chemistry--Physical and Theoretical Chemistry)

517918 AD-A028 872/0
Polyphosphazene Wire Coverings
(Final rept. 31 Mar 75-30 Mar 76)
Reynard, Kennard A. ; Vicic, John C.
Horizons Inc Cleveland Ohio
Corp. Source Codes: 408304
Jun 76 47p
See also report dated Mar 74, AD-781 578.
NTIS Prices: PC A03/MF A01 Journal Announcement: GRAI7622
Contract No.: N00024-75-C-4402; SF543-706; SF543-706-04; 17020

A 2:3 ((C6H5O)2PN- (4-C2H5C6H4O)2PN)n copolymer was selected from several candidates for compounding studies to develop fire-retardant electrical wire insulation. All formulations prepared did not contain halogen either in the polymer or in the filler system employed. A filler system based on silane-treated hydrated alumina, magnesium hydroxide, and dicumyl peroxide proved to be very effective. Formulations based on this recipe gave: (1) tensile strength and elongations greater than 1000 psi and 100%, respectively; (2) dielectric constants less than 4.5 (at 100 kHz); (3) dielectric strengths greater than 800 volts/mil; (4) NBS smoke densities of 65 and 22 in the flaming and nonflaming modes, respectively; and (5) Limiting Oxygen Index values in the range of 34-40. Samples were submitted for an evaluation of flame spread index and a value of 11 was obtained for the only sample tested to date. These values met or exceeded contract goals with the exception of the elongation, which was somewhat low, but within acceptable limits. Other formulations gave lower dielectric constant and higher elongation, but there was some sacrifice in smoke density values.

Descriptors: •Inorganic polymers; •Elastomers; Thermal stability; Mechanical properties; Phosphazene; Copolymers; Electrical insulation; Fire resistant coatings; Tensile properties; Physical properties; Synthesis(Chemistry); Polymerization; Performance tests; Aging(Materials); Crosslinking(Chemistry); Plastics

Identifiers: Terpolymers; •Poly(nitrilo-phosphoranylylidene) ; •Poly(nitrilo-phosphoranylylidene/bis(ethyl-phenoxy)); NTIS-DODN

Section Headings: 11J (Materials--Rubbers); 11I (Materials--Plastics); 7C (Chemistry--Organic Chemistry); 71H (Materials Sciences--Elastomers); 71D (Materials Sciences--Plastics); 99C (Chemistry--Polymer Chemistry)

922837 PB82-231036
Laser Induced Deposition of Thin Films (Annual Report)
(Final rept. Apr 81-May 82)
Haggerty, John S.
Massachusetts Inst. of Tech., Cambridge. Energy Lab.
Corp. Source Codes: 001450229
Sponsor: Minnesota Mining and Mfg. Co., St. Paul.
Report No.: MIT-EL-82-022
May 82 46p
Sponsored in part by Minnesota Mining and Mfg. Co., St. Paul.
Languages: English
NTIS Prices: PC A03/MF A01 Journal Announcement: GRAI8221
Country of Publication: United States

A new chemical vapor deposition (CVD) process has been demonstrated with Si thin films. In this process, reactant gases are heated by absorbing light energy emitted from an IR laser. No other surfaces are heated by the reaction, thus contamination is eliminated, the state (stress, crystallinity, grain size, etc.) of the film can be controlled and unwanted heterogeneous reaction sites are eliminated. Research conducted to date has employed silane (SiH4) as a reactant and an untuned CO2 laser. Process conditions appropriate for film deposition have been defined. Deposition kinetics, film characteristics and mixed gas optical absorptivities have been measured. Deposition rates are comparable to other low pressure CVD processes (about 1-10 A/sec) but with much colder substrate temperatures being permitted. The characteristics of initial amorphous Si films indicate that they equal or exceed the quality of films deposited by highly developed plasma or reactive sputtering techniques.

Descriptors: *Semiconducting films; *Silicon; Thin films; Carbon dioxide lasers; Pyrolysis; Silanes
Identifiers: *Chemical vapor deposition; *Amorphous materials; Amorphous silicon; Laser applications; NTISMITEL
Section Headings: 13H (Mechanical, Industrial, Civil, and Marine Engineering--Industrial Processes); 20B (Physics--Crystallography); 46D (Physics--Solid State Physics); 94G (Industrial and Mechanical Engineering--Manufacturing Processes and Materials Handling)

862898 AD-A102 365/4
Structure and Properties of Polymers and Organosilanes Adsorbed Onto Oxidized Aluminum and Titanium
(Interim rept. 1 Jul 80-30 Jun 81)
Boerio, F. James
Cincinnati Univ., OH. Dept. of Materials Science and Metallurgical Engineering.
Corp. Source Codes: 006394027; 405382
1 Jul 81 56p
Languages: English
NTIS Prices: PC A04/MF A01 Journal Announcement: GRAI8124
Country of Publication: United States
Contract No.: N00014-80-C-0733

The structure of films formed by organofunctional silanes adsorbed onto aluminum, titanium, and iron mirrors from aqueous solutions was related to the effectiveness of the silanes as primers for improving the wet strength of metal-to-metal adhesive joints made from the same metals. Gamma-aminopropyltrieth-oxysilane (gamma-APS) formed smooth, continuous polysiloxane films when adsorbed onto iron from aqueous solutions at pH 8.0. Such films were extremely effective primers. Lap joints prepared from iron adherends primed with gamma-APS at pH 8.0 retained about 70% of their original strength after 60 days immersion in water at 60C while joints prepared from unprimed adherends retained only 25% of their strength. Gamma-APS was less effective when applied to iron adherends at pH 10.4 but lap joints prepared from such adherends still retained 50% of their strength after 60 days in water at 60C. Gamma-glycidoxypropyltrimethoxysilane (Gamma-GPS) formed polysiloxane films that were effective primers when adsorbed onto iron from aqueous solutions containing an acid to catalyze hydrolysis of the silane. The environmental failure of iron/epoxy lap joints was consistent with a model suggesting debonding of the adhesive a certain distance into the joint when a critical concentration of water was obtained that same distance into the joint.

Descriptors: *Adhesive bonding; *Aluminum; *Titanium; *Iron; *Coatings; *Silanes; Primers; Siloxanes; Epoxy resins; Oxides; Films
Identifiers: Silane/gamma-aminopropyltriethoxy; Silane/gamma-glycidoxypropyltrimethoxy; NTISDODXA; NTISDODXA
Section Headings: 13H (Mechanical, Industrial, Civil, and Marine Engineering--Industrial Processes); 11C (Materials--Coatings, Colorants, and Finishes); 71E (Materials Sciences--Coatings, Colorants, and Finishes); 94G (Industrial and Mechanical Engineering--Manufacturing Processes and Materials Handling)

293040 AD-875 321
Manufacturing Techniques for Controlled Deposition and Application of Doped Oxides
(Final technical rept. 1 Mar 68-30 Dec 69)
Mayer, Alfred ; Puotinen, David A. ; Strater, Kurt
RCA Electronic Components, Somerville, N.J. Advanced Technology Lab.
Corp. Source Codes: 405199
Report No.: AFML-TR-70-191
Sep 70 134p
Distribution Limitation now Removed.
NTIS Prices: PC E05/MF A01 Journal Announcement: GRAI7221
Contract No.: F33615-68-C-1202; AF-511-8

Considerable progress was made toward the establishment of the manufacturing processes for a fully controlled doped-oxide diffusion system. The basis for this development was the study of the chemistry and kinetics of the oxidation of silane, phosphine, and diborane. A greatly improved gas handling and dilution system was designed and introduced into the manufacturing area. A close-spaced horizontal deposition reactor was developed. This is a cold-wall all-metal system with no moving parts, in which SiO2 layers can be deposited on 28 2-inch-diameter wafers at a rate of 400A to 800A per minute at 280C to 350C. (Author)

Descriptors: *Silicon dioxide; *Vapor plating ; *Silanes; *Oxidation ; *Phosphine; Oxidation ; *Diboranes; Oxidation ; Deposition; Semiconductors; Spectra(Infrared); Mass spectroscopy; X-ray spectroscopy; Doping; Manufacturing methods; Diffusion; Reaction kinetics; Diffusion coating

Identifiers: *Chemical vapor deposition; Vapor deposition; NTISAF

Section Headings: 7D (Chemistry--Physical Chemistry); 13H (Mechanical, Industrial, Civil, and Marine Engineering--Industrial Processes); 59G (Chemistry--Physical Chemistry); 69I (Industrial and Mechanical Engineering--Manufacturing Processes)

983445 DE83007551
Rf Plasma Synthesis of Ultrafine, Ultrapure Silicon Carbide Powder
Hollabaugh, C. M. ; Hull, D. E. ; Newkirk, L. R. ; Petrovic, J. J.
Los Alamos National Lab., NM.
Corp. Source Codes: 072735000; 9512470
Sponsor: Department of Energy, Washington, DC.
Report No.: LA-UR-83-367; CONF-830215-2
1983 18p
International conference on ultrastructure processing of ceramics, glasses and composites, Gainesville, FL, USA, 14 Feb 1983.
Languages: English Document Type: Conference proceeding
NTIS Prices: PC A02/MF A01 Journal Announcement: GRAI8316 ; NSA0800
Country of Publication: United States
Contract No.: W-7405-ENG-36
Ultrafine, ultrapure silicon carbide powder has been produced by reaction of silane and methane in a high temperature rf plasma. Preliminary studies include the effect of gas composition and of powder (plasma temperature) on the stoichiometry of the powder. The carbon-to-silicon ratio of the powder was varied from 1.0 to 1.9 by changing the process conditions. The powder has a BET surface area of 101 m exp 2 /g, which is equivalent to a particle diameter of 18.5 nm. A particle size in the range of 10 to 20 nm was measured by transmission electron microscopy. X-ray diffraction results indicate a domain size of 7.5 nm and a crystal structure of beta (cubic) silicon carbide. Spectrographic analysis shows that metallic impurities are lower than high quality grade commercial powder. Because of the high surface area, the powder must be stored and processed in an inert atmosphere to prevent severe contamination with oxygen. (ERA citation 08:021125)
Descriptors: *Silicon carbides; Powders; Synthesis; Silanes; Methane; Plasma; Surface area; Particle size; X-ray diffraction; Crystal structure
Identifiers: ERDA/360201; NTISDE
Section Headings: 11B (Materials--Ceramics, Refractories, and Glasses); 7A (Chemistry--Chemical Engineering); 71D (Materials Sciences--Ceramics, Refractories, and Glass); 99B (Chemistry--Industrial Chemistry and Chemical Process Engineering)

981577 AD-A127 343/2
Organosilicon Chemistry
(Final rept. 1 Oct 79-30 Dec 82)
Weber, William P.
University of Southern California, Los Angeles. Dept. of Chemistry.
Corp. Source Codes: 016356004; 361555
Sponsor: Air Force Office of Scientific Research, Bolling AFB, DC.
Report No.: AFOSR-TR-83-0242
Dec 82 14p
Languages: English
NTIS Prices: PC A02/MF A01 Journal Announcement: GRAI8316
Country of Publication: United States
Contract No.: AFOSR-80-0006; 2303; B2
Several new aspects of the chemistry of silylenes, divalent reactive silicon intermediates, have been explored. Insertion reactions of dimethylsilylene into O-H bonds of primary, secondary, and tertiary alcohols were studied. This provides an efficient route to alkoxydimethylsilanes. It was found that solvent significantly affects the reactivity of dimethylsilylene in such insertion reactions. The insertion of dimethylsilylene into Si-O bonds of alkoxysilanes permits the synthesis of a novel series of cyclic polysilanes. New insertion reactions of dimethyldilylene into silicon-sulfur and sulfur-sulfur bonds were discovered. In the chemistry of siloxane oligomers it was found that secondary and tertiary alkyl lithium reagents will add to the carbon-carbon bond of vinyl di-or trisiloxanes at low temperatures to yeild alpha-lithio di-or trisiloxanes at low temperatures to yield alpha-lithio di-or trisiloxanes with no attack by the alkyl lithium reagent on the siloxane bond.
Descriptors: *Organometallic compounds; *Chemical reactions; *Silicon compounds; *Alcohols; Hydroxyl radicals; Siloxanes; Alkoxy radicals; Methyl radicals; Solvents; Reactivities; Polysilanes; Chemical bonds; Sulfur; Alkyl radicals; Lithium; Cyclic compounds; Ethers; Hexanes
Identifiers: Silyene/dimethyl; Silane/alkoxy-dimethyl; NTISDODXA; NTISDODAF
Section Headings: 7D (Chemistry--Physical Chemistry); 99F (Chemistry--Physical and Theoretical Chemistry)

976836 N83-18727/8
Ignition of SIH4-H2-O2-N2 Behind Reflected Shock Waves
McLain, A. G. ; Jachimowski, C. J. ; Rogers, R. C.
National Aeronautics and Space Administration, Hampton, VA. Langley Research Center.
Corp. Source Codes: 019041001; ND210491
Report No.: NAS 1.60:2114; L-15534; NASA-TP-2114
Feb 83 17p
Languages: English
NTIS Prices: PC A02/MF A01 Journal Announcement: GRAI8314 ; STAR2109
Country of Publication: United States
The ignition of mixtures of silane, hydrogen, and oxygen diluted with nitrogen was studied in a chemical kinetic shock tube. Ignition delay time measurements were made behind reflected shock waves at pressures of 1.25 atm and 1.35 atm and temperatures ranging from approximately 800 K to 1050 K for two mixtures with silane-oxygen equivalence ratios of 1.0 and 0.5, respectively. Enhancement of the ignition by use of silane was observed experimentally by the failure of a similar mixture containing only hydrogen, oxygen, and nitrogen to ignite during the maximum test time available for these test conditions.
Descriptors: •Hydrogen; •Ignition; •Mixtures; •Oxygen; •Reaction kinetics; •Shock waves; •Silanes; Combustion; Computer programs; Pressure sensors; Shock tubes; Transducers
Identifiers: NTISNASA
Section Headings: 21D (Propulsion and Fuels--Fuels); 7D (Chemistry--Physical Chemistry); 97K (Energy--Fuels); 99F (Chemistry--Physical and Theoretical Chemistry)

951752 AD-A120 442/9
Exactly Alternating Silarylene-Siloxane Polymers. 4. Step-Growth Polymerization Reactions with Dichlorosilane Monomers
Lai, Yu-Chin ; Dvornic, Petar R. ; Lenz, Robert W.
Massachusetts Univ., Amherst. Goessmann Lab.
Corp. Source Codes: 010574089; 405112
Report No.: ONR-TR-10
16 Dec 81 14p
Pub. in Jnl. of Polymers Science: Polymer Chemistry Edition, v20 p2277-2288 1982. See also AD-A114 852.
Languages: English Document Type: Journal article
NTIS Prices: PC A02/MF A01 Journal Announcement: GRAI8307
Country of Publication: United States
Contract No.: N00014-76-C-0700
No abstract available.
Descriptors: •Synthesis(Chemistry); •Siloxanes; Epitaxial growth; Polymerization; Aryl radicals; Polymers; Monomers; Silanes; Thermal stability; Chemical reactions; Reprints
Identifiers: Silane/dichloro; NTISDODXR
Section Headings: 7C (Chemistry--Organic Chemistry); 11I (Materials--Plastics); 99C (Chemistry--Polymer Chemistry); 71O (Materials Sciences--Plastics)

944373 PB83-109496
Dehydroabietaan en Podocarpaan (Dehydroabietane and Podocarpaine)
van Herwijnen, Peter R. A. ; Godefroi, E. F. ; Janssen, C. G. M.
Technische Hogeschool, Eindhoven (Netherlands). Lab. voor Organische Chemie.
Corp. Source Codes: 021023007
16 Jun 82 55p
Text in Dutch.
Languages: Dutch
NTIS Prices: PC A04/MF A01 Journal Announcement: GRAI8303
Country of Publication: Netherlands
Dehydroabitane and podocarpaine belong to the diterpane group and form the main component of certain conifer and pine tree resins. A problem in total synthesis arises mostly from the stereo-chemical aspects as well as the trans-A/B-binding and configuration about C-4. In supplementary experiments with substitute aromatic silane systems the inductive effect of trimethylsilyl substitute in electrophile substitutions is being studied.
Descriptors: •Synthesis(Chemistry); Pine trees
Identifiers: •Foreign technology; •Abietane/dehydro; •Podocarpaine; NTISTFNPO
Section Headings: 7C (Chemistry--Organic Chemistry); 99D (Chemistry--Basic and Synthetic Chemistry)

dPmaim

99063584 CA: 99(8)63584h JOURNAL
Preparation and study of reverse phase chromatographic packing materials
AUTHOR: Ohmacht, Robert
LOCATION: Kem. Intez., POTE, 7643, Pecs, Hung.
JOURNAL: Magy. Kem. Foly. DATE: 1983 VOLUME: 89 NUMBER: 5 PAGES: 229-32 CODEN: MGKFA3 ISSN: 0025-0155
LANGUAGE: Hungarian
SECTION:
CA180003 Organic Analytical Chemistry
CA121XXX General Organic Chemistry
CA166XXX Surface Chemistry and Colloids
IDENTIFIERS: reversed phase packing liq chromatog, high performance liq chromatog packing, silica gel chlorooctadecylsilane reaction product, ethylamine capping silica gel packing, chlorosilane capping silica gel packing, silazane capping silica gel packing

99062315 CA: 99(8)62315j JOURNAL
Mass-spectrometric studies of impurities in silane and their effects on the electronic properties of hydrogenated amorphous silicon
AUTHOR: Corderman, R. R.; Vanier, P. E.
LOCATION: Div. Metall. Mater. Sci., Brookhaven Natl. Lab., Upton, NY, 11973, USA
JOURNAL: J. Appl. Phys. DATE: 1983 VOLUME: 54 NUMBER: 7 PAGES: 3987-92 CODEN: JAPIAU ISSN: 0021-8979
LANGUAGE: English
SECTION:
CA176001 Electric Phenomena
CA152XXX Electrochemical, Radiational, and Thermal Energy Technology
IDENTIFIERS: hydrogenated amorphous silicon deposition, silane glow discharge decompn, impurity silane silicon deposition, cond hydrogenated amorphous silicon, Fermi level amorphous silicon, solar cell amorphous hydrogenated silicon

99060788 CA: 99(8)60788s JOURNAL
Properties of chemically derivatized nickel electrodes: the synthesis of an electrocatalytic interface
AUTHOR: Bocarsly, Andrew B.; Galvin, Sharon A.; Sinha, Sujit
LOCATION: Frick Lab., Princeton Univ., Princeton, NJ, 08544, USA
JOURNAL: J. Electrochem. Soc. DATE: 1983 VOLUME: 130 NUMBER: 6 PAGES: 1319-25 CODEN: JESOAN ISSN: 0013-4651 LANGUAGE: English
SECTION:
CA172002 Electrochemistry
CA129XXX Organometallic and Organometalloidal Compounds
CA167XXX Catalysis, Reaction Kinetics, and Inorganic Reaction Mechanisms
CA178XXX Inorganic Chemicals and Reactions
IDENTIFIERS: nickel electrode chem modified, silane iron contg modified electrode, silanized nickel electrode, electrocatalyst iron contg silane ferrocene, ferrocene electrooxidn catalyst

99056183 CA: 99(8)56183y TECHNICAL REPORT
Laboratory tests at elevated pressures of a silane igniter system for in-situ coal gasification
AUTHOR: Thorsness, C. B.; Skinner, D. F.; Fields, D. B.
LOCATION: Lawrence Livermore Natl. Lab., Livermore, CA, USA
JOURNAL: Report DATE: 1982 NUMBER: UCRL-53361; Order No. DE83007217 PAGES: 32 pp. CODEN: D3REP3 LANGUAGE: English CITATION: Energy Res. Abstr. 1983, 8(8), Abstr. No. 17067 AVAIL: NTIS
SECTION:
CA151020 Fossil Fuels, Derivatives, and Related Products
IDENTIFIERS: coal gasification underground silane igniter

99055886 CA: 99(8)55886t CONFERENCE PROCEEDING
Effect of hydrolysis of organosilicon compounds on their fire extinguishing
AUTHOR: Belyaev, S. V.; Dolgov, E. I.; Nazarov, N. I.; Sukhov, I. Ya.
LOCATION: USSR
JOURNAL: Gorenie Probl. Tushenlya Pozharov, Mater. Vses. Nauchno-Prakt. Konf., 7th EDITOR: Baratov, A. N (Ed) DATE: 1981 NUMBER: Probl. Tushenlya Pozharov Razrab. Ognetushashchikh Sostavov PAGES: 15-18 CODEN: 49NZAJ
LANGUAGE: Russian PUBLISHER: Vses. Nauchno-Issled. Inst. Protivopozharnoi Oborony, Moscow, USSR
SECTION:
CA150006 Propellants and Explosives
IDENTIFIERS: fire extinguishing silane siloxane hydrolysis, silane fire extinguishing hydrolysis effect

99055843 CA: 99(8)55843b PATENT
Monosilane purification
LOCATION: Japan
ASSIGNEE: Mitsui Toatsu Chemicals, Inc.
PATENT: Japan Kokai Tokkyo Koho ; JP 8369715 A2 ; JP 5869715
DATE: 830426
APPLICATION: JP 81167284 (811021)
PAGES: 5 pp. CODEN: JKXXAF LANGUAGE: Japanese
CLASS: C01B-033/04
SECTION:
CA149008 Industrial Inorganic Chemicals
IDENTIFIERS: silane purifn, chlorosilane removal silane, zeolite 4A purifn silane, active carbon purifn silane

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AN INVESTIGATION OF LUNAR PRODUCTION OF SILANE

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17629 El Camino Real
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September 26, 1983

TO-83-26

Report #83-74

Appendix C

INTRODUCTION

The use of lunar materials in support of space missions has received considerable attention(1). Elaborate flow diagrams have been developed that show integrated schemes for producing a large number of elements and compounds from lunar soil.

The present study has a more limited scope. It is concerned with the lunar production of silane as a propellant for transport of oxygen from the lunar surface to refuel stations in Earth orbit. The oxygen will be produced from Ilmenite ($FeTiO_3$). Hydrogen will be transported from Earth for both the silane production and for the reduction of Ilmenite. It is desirable to eliminate or minimize the need to transport any raw materials from Earth for the lunar production of silane.

Silanes are compounds containing a hydrogen-silicon bond. The simple inorganic silanes are similar to carbon in that they form stable, covalent, single bonds(2). The inorganic silanes are analogous to the paraffin hydrocarbons in chemical formula and physical properties.* Boiling points, melting points, and dipole moments are comparable. Both silanes and hydrocarbons are colorless gases or liquids at room temperature. The similarity ends with the simple physical properties(2). Silane is pyrophoric, igniting immediately on contact with oxygen.

Silanes have less thermal stability than their hydrocarbon analogs. The C-H bond energy in methane is 414 kJ/mol (98.9

*The simplest silane is SiH_4, and is generally called silane, but is also sometimes referred to as monosilane, silicon tetrahydride, and silicane.

SUMMARY

A brief investigation of silane production on the lunar surface has shown that a number of approaches are possible. The silicides of magnesium and iron will react with mineral acid or water to form silane. Most silane is made commercially from the triclorosilane, $HSiCl_3$, by a number of processes.

It is recommended that an effort be made to determine more details of commercially practiced silane technology and then to evaluate the transferability to the lunar environment. Also, consideration of the integration of the silane process with other lunar operations, such as ilmenite reduction or HF acid-leaching, should be considered.

kcal/mol) compared to 364 kJ/mol (87 kcal/mol) for each Si-H bond in silane. Silane, however, is one of the most thermally stable inorganic silanes. It decomposes at 500°C in the absence of catalytic surfaces. The thermal decomposition of the silanes in the presence of hydrogen into silicon for production of ultrapure, semiconductor-grade silicon is known as the Seimens process.

PROPERTIES

Properties of silane are shown in Table 1. These data were obtained from several sources[1, 2, 3, 4]. The vapor pressure data were calculated from the equation shown.

PRODUCTION OF SILANE

Trichlorosilane ($HSiCl_3$) is the only inorganic silicon hydride produced in large scale. Total U.S. production is ca. 30,000 metric tons[2]. Silane production has been <10 T/yr, but Union Carbide has a new plant estimated at 100 T/yr. The Union Carbide process is thought to be based on catalytic disproportionation reactions of chlorosilanes resulting from the reaction of hydrogen, metallurgical silicon, and silicon tetrachloride[5]:

$$Si + SiCl_4 + H_2 \;\; \text{cat.} \;\; HSiCl_3 + \text{byproducts}$$

$$4\, HSiCl_3 \xrightarrow{\text{cat.}} SiH_4 + 3\, SiCl_4 + \text{byproducts}$$

A proposed process is shown in Figure 1[2]. Other common catalysts in order of decreasing reactivity are halides of aluminum, boron, zinc and iron[2].

High purity trichlorosilane is usually produced in a fluidized bed at 300-450°C.

$$Si + 3\ HCl \quad SiHCl_3 + H_2$$

Substantial amounts of silicon tetrachloride also form in the process.

Inorganic silanes have traditionally been produced from silicides.[1]

$$Mg_2Si + 4\ HCL \quad SiH_4 + 2\ MgCl_2$$

A disadvantage to this reaction of acid with magnesium silicide is the requirement of transport of the mineral acid from earth. Under proper conditions, silicides will react with water[6]:

$$Mg_2 + 4\ H_2O \quad SiH_4 + 2\ Mg(OH)_2$$

This would utilize water from the ilmenite process as the hydrogen source. The magnesium hydroxide could be decomposed by heat to recover water in order to prevent loss of hydrogen and oxygen in the byproduct $Mg(OH)_2$. The <u>overall</u> reaction would be:

$$Mg_2Si + 2H_2O \quad SiH_4 + 2MgO$$

Since metallic iron is a byproduct of the ilmenite process, the use of iron silicides would provide process integration. Iron silicides can be produced by direct combination at high temperature. These materials are produced in the metallurgical industry by combining the elements in molten baths using electric furnaces. A number of iron silicides can be formed (Fe_5Si_3, FeSi, $FeSi_2$, Fe_2Si_5, etc.)[7]. Thermodynamic data indicate that FeSi formation is more favorable at 1000°K than at 1600°K[1]. References have been found to reactions of iron silicides with acids or their ammonium salts to produce silane[2]. Mack[6] mentions the hydrolysis of magnesium silicide to form silane. However, no references were found to the hydrolysis reaction of any of the iron silicides.

An interesting reaction that might be worth investigating is the direct hydrogenation of silicon chloride in the presence of metallic aluminum[2]:

$$3\ SiCl_4 + 4\ Al + 6\ H_2 \rightarrow SiH_4 + 4\ AlCl_3$$

The recycling of the $AlCl_3$ and the production of $SiCl_4$ could possibly result in a closed cycle.

The use of an HF acid-leach process to recover lunar elements has been described[8]. This process offers interesting silicon chemistry because fluorine is the only element that bonds more strongly with silicon than does oxygen. Thus, silicates react with fluorides or HF to form volatile SiF_4, which can be converted to silane by reaction with metal hydrides[1]:

$$SiF_4 + LiH \rightarrow SiH_4 + LiF$$

Lithium aluminum hydride is used to reduce chlorosilanes[2]:

$$HSiCl_3 + LiAlH \rightarrow SiH_4 + LiCl + AlCl_3$$

The development of a closed cycle using the metal hydrides that would be simple enough to use on the Moon does not appear probable.

Table II contains a series of chemical reactions that show an integrated approach to the production of silane and oxygen from ilmenite, silicon dioxide, and water. Since the amount of ilmenite used in the production of silane is only a fraction of the total ilmenite converted in the oxygen process, the silane process will not be used in a stand-alone manner. In practice, water from the ilmenite process would be used with the silicide, and the iron would be used to prepare the silicide. This form of iron silicide forms an attractive reaction for the overall integrated process. However, the reactivity in this scheme is not known, for no information has been found in the literature.

The process shown for the conversion of silicon dioxide to silicon uses the HF step and hydrogenation of the silicon tetrafluoride. Some care must be taken because HF can attack the silicon, thus lowering the yield[9]. Other schemes may be better for obtaining silicon for silicide production[7].

CONCLUSIONS

- The properties of silane, SiH_4, indicate that it could be handled by cryogenic techniques and would be compatible with liquid oxygen as a propellant.
- A cursory examination of the literature does not reveal an obviously superior process for lunar production of silane.
- A number of processes would appear to be feasible for lunar use.

RECOMMENDATIONS

1. Develop more complete details for the more commonly practiced processes for silane production. After details are

obtained, determine the practicability of using each process at a lunar facility.

2. Investigate non-commercial reaction schemes from the literature. It is quite possible that a process that is not economically competitive on Earth may offer advantages for operations on the Moon.
3. Integrate silane process with ilmenite and other potential lunar processes.